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Avian Attractiveness to Vertically Polarized Light

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Recommended Citation

Kuczek, Aurora Belle, "Avian Attractiveness to Vertically Polarized Light" (2021). *Senior Projects Spring 2021*. 205.
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Avian Attractiveness to Vertically Polarized Light

Senior Project Submitted to
The Division of Social Sciences
of Bard College

by
Aurora Belle Kuczek

Annandale-on-Hudson, New York
May 2021

Abstract

It is well-known that many animal species can detect polarized light cues of water and water-like objects in the visible and ultraviolet range. However, studies investigating if birds can see polarized light in field-based settings are rare. Furthermore, no studies have yet been conducted to understand avian attractiveness to vertically polarized light, nor have studies considered other natural polarizers of light such as tree sap. I designed a choice-field experiment to investigate if birds can detect, and are attracted to vertically polarized light. First, I cut six pieces of clear vinyl into a foot by 54 inches. I painted each vinyl sheet with Black 3.0, advertised as the blackest paint in the world. Two treatments were wrapped around two trees similar in dbh (<40 dbh) and close in distance (<5 feet): one had shiny exposed, and the other matte, painted side, exposed. Suet feeders were hung directly below each treatment on both trees. Two remote cameras were placed on a fence post away from both tree (10 feet in fall; 6 feet in spring). The suet feeder height, camera distance, and the height of both vinyl stayed the same. These treatments were exposed to birds. A baseline study was conducted before installation of treatments to understand bird biases or preferences to one tree position over the other. I made conclusions about birds being able to see, and their attraction to, vertically polarized light by capturing and counting visitations from images, and comparing treatments' bird visits over a designated period of time. My results revealed that birds are able to detect and are attracted to vertically polarized light, and use it to guide foraging behavior. Attraction to polarized light is dependent upon the location of the site, as well as the position (left or right tree), and certain species may play a role in these conclusions, though they do not overwhelm the data. The baseline study to treatment comparison reveals that any preferences to one position over the other were eliminated when treatments were added, and the polarized, shiny treatment had more of a signal than the matte treatment when each treatment were compared separately to the baseline. These results suggest a need to expand site-wise across various habitats to understand the effects of site location, to understand the effects of the positionality of treatments on different species of trees, and to understand how different species may have an effect on treatment visitation. Sap was imaged using a polarimeter to understand if natural Maple sap polarizes light compared to my polarized proxy for sap. My analyses reveal that natural Maple sap polarizes light, and this is strongest in the ultraviolet range. My treatments polarize a high degree of light in both the visible and ultraviolet range, making it an effective simulator of natural Maple sap. This exciting discovery gives insight on how birds may navigate a complex landscape according to polarized cues of that landscape (polarization of sap), and how they use these cues to facilitate their foraging behavior (eating sap).

Dedication

I would like to dedicate this research to my favorite being on this planet who sadly passed away before I could say goodbye. My cat Batman—thank you for being there for me for over seventeen years. Though you killed birds and knew I didn't like that, I still loved you. You always brought me outside even when it was snowing and cold. Thank you for drinking out of the bird bath when you had a water bowl, and eating insects sporadically.

I would also like to dedicate this to the frozen Wood frog I buried in a jewelry box many years ago. Years later, I discovered that some species of frogs hibernate and essentially turn to stone. I felt as though this frog never received the recognition it deserved.

Acknowledgements

☽ Bruce Robertson ☾

~Thank you for your patience, wisdom, thoughtfulness, much needed bird humor and encouragement during these long semesters. Not only did you help me to further and hone my academic and scientific skills, but you also inspired me to reach outside my comfort zone and grasp new feathers along the way. I learned more than I could have imagined, and I will remember your fantastical field stories~

☽ Cathy Collins ☾

~In the fields outside Manor, I understood that science doesn't have to be so dry as I was taught as so years before. I learned that Nature has an unquenchable vivacity: no matter how much we study, there will always be more connections, and more languages to decipher. Thank you for your wisdom, your kindness, your enthusiasm, and your pure love for the natural world~

☽ Karen Sullivan ☾

~Two years ago, a curious email about an old and mystical language led me to embark on a truly wonderous—perhaps Viking—journey to the land of fire and ice. My gratitude is profound: thank you for helping me to explore, write and speak Old Norse, to read the Sagas, and to allow me to understand a world gifted in magic. I carry this with me wherever I go, and will never forget your incredible wisdom, your words, and your stories~

☽ Susan Rogers ☾

~Thank you for teaching me the love I now have for birds, and long walks in Nature searching for them. Your writing has inspired me beyond any words can express, and you brought me back years to the works of true naturalists, who are now on the brink of extinction. This I hold with me today~

☽ Benjamin Hale ☾

~You encouraged me to write without barriers, to draw ideas from the wildest of searches, and learn how to read properly before beginning to step foot in the realm of writing. One of my favorite moments over the years is reading Beowulf in front of a campfire for Imagining Nonhuman Consciousness. Thank you for helping me hone my writing skills, and furthering strange ideas~

☽ Erik Kiviat ☾

~Thank you endlessly for your naturalist wisdom and research. Though a short internship, the diverse range of skills I learned through Hudsonia were crucial in furthering my scientific understanding of the world around me. I still remember when we took canoes to see Northern cricket frogs as the sun set: arguably the most fascinating and peaceful experiences~

☽ Arseny Khakhalin and Eli Dueker ☾

~Thank you immensely for your analytical knowledge and ideas in helping me study complexities in the bird world. Your questions challenged me to think in different ways, and your kindness in this process was more than I could have asked~

Contents

1 Background

1.1 A Viking Discovery

From the late eighth to early eleventh century, lived the age of the Vikings. Though given a brutal portrayal by modern writers and producers, the Vikings were skillful people. They created an intricate society that included their language of Old Norse, their stories written in sagas[1], their mythologies, and a division of labor and law. The men participated in tasks that were "hard" duties, such as being a farmer, while women participated in tasks that were "soft" duties, such as sewing and other household practices. Women in Viking societies were excellent seamstresses, creating practical clothing made out of wool and natural fibers (Mannering, 2016) for the harsh, cold weather they faced. The Vikings were experienced farmers, knowing how to tend to and respect their land. Some were raiders who conquered many foreign lands in search of riches and conquest, sometimes taking slaves home with them. But above all, the Vikings were knowledgeable seafarers. This allowed them to efficiently travel the vastly unknown ocean, and reign the seas for hundreds of years.

The *Saga of Erik the Red* and the *Grœnlendinga Saga* documents the extraordinary journey of such seafarers including Leif Erikson, Erik the Red's son. Erik the Red, in order to escape famine in Iceland, lured settlers from Norway to Greenland through the appealing name of the continent. But Greenland's climate was rather inhospitable compared to Iceland.

The navigation from Norway to Greenland was travelled along 61 degrees North latitude—one of the most important travel routes during the Viking day (Horváth et al., 2011). Bjarni Herjólfsson, an Icelander, embarked on this travel route to Greenland but was soon set off

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[1] Sagas were thought to be recorded by people like Snorri Sturluson, a poet and politician, rather than the Vikings themselves. Thus, Viking life written in the sagas could be an interpretation based upon observers, rather than a first person account.

course. During this journey, he sighted a strange new land that was not Greenland (Smiley 2005). Historians who have studied the sagas theorize that he supposedly sailed near the coastline of North America before returning to Greenland. After hearing about this new land, Leif Erikson, Erik the Red's son, set off to find the land that Bjarni had seen. They were successful in their search. Leif Erikson and his crew stepped foot onto the land they called Vinland. His fleet included Gudrid Thorbjarnardóttir, the first woman who set foot onto this new land. Vinland is thought to be the present day archeological Viking site of Newfoundland (Smiley 2005). According to the sagas, these Icelanders discovered the Americas long before Christopher Columbus. Where the Vikings went next is largely unknown.

These brave Vikings navigated the Atlantic Ocean to reach the Americas using skills and tools made from the environment to guide them. The Viking sagas are comparable to documented historical events, which means that the sagas can be used as a representation of historical accuracy. In this way, text from the sagas can give current researchers insight into the makeup of their society, including the discoveries they made. Archeological finds point to a Viking sundial, but this can only be used for navigation when the sun shines (Horváth et al., 2011). Archeologist, Thorkild Ramskou, first theorized in the 1960s that the Vikings navigated such strong seas using a sunstone (Ramskou 1967). A sunstone is a crystal that, when light waves coming from the sun interact with the stone, produces a double image pattern that can be used for compass direction. The specific stone used by Vikings is unknown (Horváth et al., 2011), but is thought to be comprised of Iceland spar, or calcite (Rospars 2012). This stone can also be used when the sun is not shining or if there are no direct polarization cues from the sky. The Vikings would rotate the crystal while looking at the sky through the crystal, as the sky is partially polarized. The Vikings would scrape a line in the stone pointing to the direction of the sun through a clear patch of sky. They would then rotate it again until the sky is the brightest. This would be associated with the direction of the sun when it is not visible to the Vikings (i.e., the sun obscured by clouds). Parallel to the scratches on the sunstone, there would be two 'circles' produced by the stones ability to produce a double image. Where the circles intersect would be the position of the sun (Horváth et al., 2011).

To understand more of the Viking voyage process, a modern-day, extensive study was conducted. Száz & Horváth (2018) simulated 1000 Viking voyages during a three week-long journey across the 61 degree North latitude route the Vikings were known to travel. Researchers used calcite, cordierite and tourmaline—three different types of crystals the Vikings could have used—to navigate strong seas. Overall, the study found that the time of day mattered in relation to the position of the sun and the position of North. This means that the Vikings must have used the crystal every three hours with respect to real noon to make sure they stayed on the same route. Furthermore, even without a magnetic compass, the Vikings were able to navigate the seas using the polarization from the sky (Száz & Horváth 2018).

It was the Vikings who stirred the waters in a mysterious discovery, a tale unbeknownst to many, but largely comprises much of the natural world. This was the discovery of a phenomenon known as *polarized light.*

1.2 Polarization

What the Vikings found would change the way ecological scientists, as well as physicists, would look at the Earth and its inhabitants. Many years after the Vikings, arose a man by the name of Erasmus Bartholin (1625-1698). In 1669, he created the first publication of polarized light. Similar to what Ramskou theorized about the Vikings, Bartholin obtained Icelandic spar and carefully studied the mineral's properties. He also found that the stone had double refraction: the differentiation from ordinary rays and extraordinary rays from a rotating image (Goldstein 2017). Though crucial in his findings, this was only the beginning to the wave of polarized knowledge that is still being studied today.

Polarization, by definition, is when waves from an object are forced into a singular direction. A wave is essentially a transfer of energy from one point to another point through a medium. These waves, electromagnetic in nature, will vibrate in the direction of propagation (Können 1985). Imagine a slightly stretched slinky is placed on a table from the left of the table to the right side, and your hands slightly brace both ends. If you move your left hand slightly to the right and then move it back to its original position, you will see a movement of the slinky that moves from the left to the right and back to the left across the surface of the table. This occurs in oscillations across a *horizontal* surface. Now take the slinky and coil it up. Standing and holding the slinky in one hand facing toward the ground, let go of the bottom coils while holding on to the upper ones. This produces a similar oscillation but in the direction that is *vertical*. The slinky moves downwards to the floor and back up to your hand until it reaches to a resting position. This is an example of what a wave could look like, but it is also shows the importance of the direction of the wave (i.e. movement from the left hand to the right hand (horizontal) or the movement down the floor and up back towards the hand (vertical)).

Polarized light, in small terminology, has to do partly with photons. Photons are particles of light that carries light energy from one place to another. When they travel, they have a randomized axis. Partially polarized light can be produced through absorption, reflection or scattering (Cronin et al., 2011). Partially linear polarized light is defined by the intensity, degree, and angle of polarization (Horváth et al., 2009). When it is reflected and linearly polarized, it produces something called an electromagnetic vector or an e-vector. E-vectors are orientated in a singular plane when it is scattered (Cronin et al., 2011), and the direction of vibration is perpendicular to the scattering angle (Muheim et al., 2011). This results in visible light becoming polarized to the viewer's eye. Vectors are essentially a directionality of waves that are oscillating in a particular direction. These vectors are generally talked about in tangent with unpolarized light hitting an object and its resulting e-vector's directionality and polarization from interacting with that object. The plane containing e-vectors are located in the plane of oscillation. If it is said that an object polarizes light vertically, the e-vectors are oscillating vertically (Halliday et al., 2008).

Light, from the sun or a light bulb, can be, but is not limited to, linearly polarized, circularly polarized, partially polarized or unpolarized. When light is linearly polarized, the vibrations are within one plane (Können 1985), such as left to right (horizontal) or top to bottom (vertical). Studies investigating vertically polarized light in Nature have been less examined than horizontal polarized light. When light is circularly polarized, the light exhibits a spiral pattern as a result of a rotation, such as clockwise or counterclockwise (Können 1985). Partially polarized light exhibits oscillations that have some directionality, but also some randomness (Halliday et al., 2008). Unpolarized light is essentially waves that have randomly oriented e-vectors (Halliday et al., 2008).

Sunlight, an example of a wave, does not have directionality in its plane of vibration (Können 1985). It is made up of e-vectors that are randomly oriented and vibrating with no directionality. Thus, when light enters the earth, it is generally unpolarized (Cronin et al., 2011), but can be partially polarized (Können 1985). Partially polarized light combines linearly polarized, circularly polarized and unpolarized to create a degree of polarization in each kind of polarized form (Können 1985). Through processes of reflection and refraction off of particulates in the atmosphere, unpolarized light from the sun, the natural source for all polarized light on Earth besides the moon, can become polarized to a viewer's eye (Cronin et al., 2011).

1.2.1 *Color, Visible & Ultraviolet Light*

Different colors and surface textures polarize light differently. A Russian physicist by the name of Nikolay Umov (1846-1915), delved deep into the world of polarization. To explain the effects of polarized light, he stated that darker and smoother objects have a greater degree of linear polarization, whereas those that are matter, rougher and lighter, are a strong depolarizer of light (Horváth et al., 2014). This became known as the Rule of Umov (1905), and has been referenced by many as a 'definition' of polarized light. Thus, color and texture of an object's surface is responsible for its polarization properties.

Within the electromagnetic spectrum exist two kinds of light or radiation that is of importance to the discussion of polarized light: visible light and ultraviolet radiation or light. The primary difference between the two is UV light has a shorter wavelength than visible light, oscillating faster than in the visible spectrum. Visible light is the light that humans can perceive (red, orange, yellow, green, blue, etc.), and each color corresponds to a wavelength in nanometers. Ultraviolet light is more so purple or violet in color, and its nanometers are lower in value than visible light (Diagram 1). On the contrary, humans cannot see UV light, but it has been suggested that some animals can detect it (Cronin & Bok, 2016; Hunt et al., 2001): at least 35 species of diurnal birds, four species of rodents, 11 species of reptiles, and two species of amphibians can detect some polarization in the UV range (Honkavaara et al., 2002). Using technology like cameras with polarizing lenses in the visible and UV range can show what direction and angle photons are vibrating, and what objects successfully polarize in the different ranges of light (Hórvath et al., 2014).

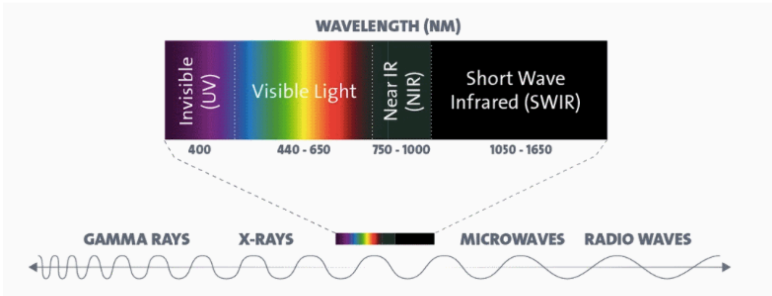

DIAGRAM 1: Ultraviolet and visible light on the electromagnetic spectrum

1.2.2 *Reflection, Absorption & Refraction*

Water is the only natural object that polarizes light.

You stand at the water's edge (Diagram 2): one hand on a kayak, and the other hand shielding your eyes from the sun. Your eyes look at a dark lake on a calm and sunny day. Visible light from the sun enters through earth's atmosphere and hits the surface of water in the form of an incident ray. As explained before, sunlight is unpolarized. There are two directions this unpolarized ray goes. Some part of that ray hits the top of the water and is reflected off of the surface of the water resulting in 100% polarization to the viewer's eye. Reflection is the process of that ray bouncing off of the surface of the water, and continuing to travel in the direction the light was first going, but this time, in a slight upwards direction. The reflected ray has perpendicular components (perpendicular to the plane of incidence), and also parallel components (parallel to the plane of incidence) (Halliday et al., 2008).

The other part of the incident ray from the sun that is not reflected, goes through the surface of the water. This sunlight is absorbed by the muddy and murky lake bed and refracted by suspended particles. Absorption occurs when light is taken in through a surface, and refraction is when that incident ray that enters the water, separates two media (Halliday et al., 2008). The darker and rougher the lake bed is, the higher the net polarization to the viewers' eye (reflection, 100% polarization plus absorption, 0% polarization, according to the Rule of Umov).

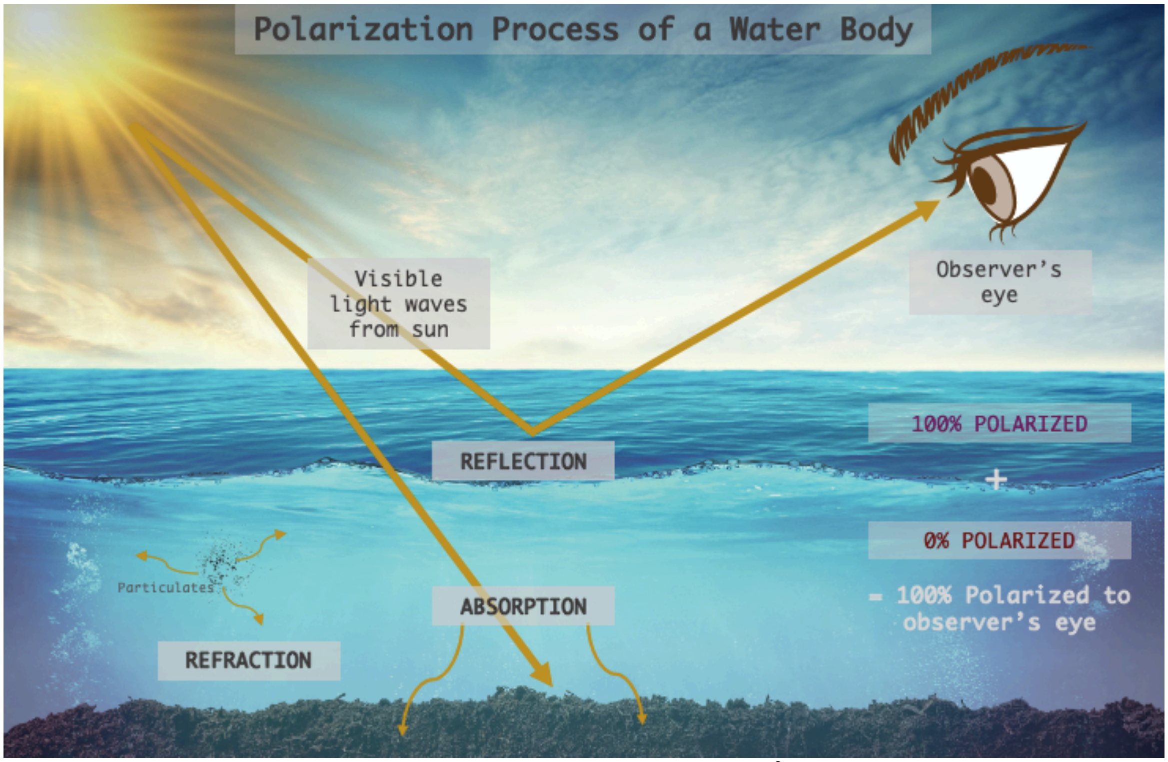

DIAGRAM 2: Visualization of polarized light of water to an observer's eye.[2]

Reflected light is partially polarized, but when it is incident at the Brewster's angle (water = 56 degrees) where light is perfectly polarized, the reflected light only has perpendicular components, where the parallel components refract into the water. If a lake bottom is very dark and muddy, the resulting effect of the combination of these two waves (reflection and absorption) to an observer at the lake shore is 100% polarization of water perpendicular to the plane of incidence (Halliday et al., 2008).

[2] Images downloaded from Shutterstock™ to make diagram.

Lighter colors and smoother surfaces reflect more light than darker colors and rougher surfaces that absorb more light. For example, a shiny and white surface, such as an ice sheet, will have the highest reflection, whereas a matte and dark surface such as an asphalt road will absorb more light. In terms of polarization, it is the *combination* of reflection and absorption to a viewer's eye that makes a surface polarized rather than just reflected or absorbed. Instead of a muddy lake bed, if there were white rocks or a flat white surface underneath the water, the overall resulting polarization to the observer's eye would be lower. If there was a flat black rock underneath the water instead of rougher rocks, the net polarization to the viewer's eye would also be lower. If the waters were turbid, meaning there were suspended particles like dirt or pollutants in the water, this would result in more refraction and absorption beneath the waters, thereby producing a greater polarization to the viewer's eye (Horváth & Varjü, 2004). Depth, turbidity, transparency, color, surface roughness, and composition below the water influences reflection, absorption and refraction processes that make a body more or less polarized (Horváth et al., 2014).

1.2.3 *Sky Scattering*

Scattering is when light is absorbed and re-radiated (Tipler 1982). In the appearance of a blue sky, air molecules scatter light in short wavelengths rather than longer wavelengths. Rayleigh scattering is essentially the scattering of light by particles smaller than the wavelength of radiation, which results at the blue end of the visible spectrum, thus making the sky blue.

The degree of linear polarization dictates a difference between cloudy, clear, overcast, smoky and tree-canopied skies (Horváth et al., 2014). Suggested that animals can see the celestial polarization patterns of the sky, a topic that is honed in my research, they are able to orient themselves due to the polarization of skylight perpendicular to the plane of scattering in the Rayleigh model (Horváth et al., 2014). Suhai and Horváth (2004) found that Rayleigh is higher for clear skies than cloudy skies. They also found that when solar elevations increase, Rayleigh is higher in the blue part of the spectrum, and lower in the green and red parts of the spectrum when the sky is clear and cloudy. During foggy conditions, sunlight is scattered on the water droplets in the sky as observed by a viewer's eye. When the sky is covered with smoke, it presents an ecological issue to polarization-sensitive animals that use the sun to navigate and to orient, similar to the Vikings.

Interestingly enough, Hegdüs et al. (2007) found that the angle of polarization of light through clouds on an overcast day is the same quantitively as the polarization pattern on clear days (Horváth et al., 2014). The sun is not the only source of natural light. The *moon* creates very similar patterns of scattering as partially polarized sunlight (Horváth et al., 2014). During twilight and early morning hours, the sun is barely visible, but it is enough to provide sufficient scattering of light through the atmosphere that animals such as birds and insects navigate and even migrate at these such times. This is because polarized light cues are the strongest and most direct. When the sun travels across the sky, its cues are less direct.

1.3 Who can see polarized light?

There is a great taxonomic diversity in the species of animals who can see polarized light, and the types of terrestrial ecosystems they inhabit. Animals such as butterflies (Reppert et al., 2004; Sauman et al., 2005; Sweeny et al., 2003), ants (Narendra 2007; Vowles 1953; Zeil et al., 2014), octopus (Shashar & Cronin 1996), frogs and frog larvae (Auburn et al., 1979; Justis & Taylor 1976; Phillips et al., 2010), crickets (Brunner & Labhart 1987; Heinze 2014; Labhart 1999), cockchafers (Hegedüs et al., 2006), fish (Berenshtein et al., 2014; Flamarique et al., 2001), newts (Landreth & Ferguson 1967), and various insects (Black & Robertson 2019; Danthanarayana & Dashper 1986; Heinze 2017; Horváth 2010; Kriska 1998; Kriska et al., 2006; Mathejczyk et al., 2019; Weir & Dickinson 2012) have been known to detect polarized light. Studies with these organisms suggest that animals can see polarize light, but propose mechanisms of animal behavior as reasoning for polarized light detection.

1.3.1 *Information polarized light provides, and how animals use it to make decisions*

Animal behavior is essentially the study of why animals do what they do, and how they go about doing it. An animal reacts to cues from their environment, and makes decisions on how to best go forward in response to these cues to survive. A cue is a signal from the environment that directs or alerts an animal about environmental stimuli. Such cues can be in relation to a predator nearby, a food source, or a potential mate. In relation to polarized light, it has been theorized that these such animals are sensitive to cues, but the behavioral mechanisms to explain why animals see polarized light are somewhat lacking. This is especially true in the case of birds.

Some of the most well-known and documented evidence of polarized light in animal vision as it relates to animal behavior have been conducted with honeybees (Esch & Burns 1996; Kraft et al., 2011; Von Frisch 1965; Zeil et al., 2014; Zolotov & Frantsevich 1973) and dung beetles (Dacke et al., 2003; Dacke 2014; Dacke et al., 2020; El Jundi et al., 2019).

One of the earliest examples of polarized light vision in animals, that has been referenced in many papers, is experiments with honeybees by ethologist, Karl Von Frisch starting in the 1920s, with his first publication in 1967. Though Aristotle first noticed a strange honeybee behavior while watching them, his observations never spurred into scientific questioning.

Von Frisch's experimental design was as follows (Von Frisch 1965): he would place two sugar bowls at two feeding stations away from a honeybee nest. The bees would investigate the sugar bowls. He then used paint to mark the bees two different colors correspondent to the different feeding stations. When the bee returned from the feeding station to the nest, von Frisch noticed they performed two sets of "dances." The round or the waggle dance provided insight to the other bees in the nest about the location of the food. The round dances from bees coming from different feeders differed in their rotation—one was clockwise, while the other was counterclockwise. The round dance is a language performed that tells other bees there is a food source within a couple of meters. The waggle dance tells information of the distance to where the food is both in time and in kilometers. Von Frisch noticed that a bee follows the sun through its dances, and furthermore found that honeybees can actually see polarized light. Due to this phenomenon, a bee will shift its orientation of its dance to match the angle of the sun, such as if the food is in the direction of the sun, the bee will dance in a straight path.

Dung beetles are another example of an animal (insect) who can see polarized light. The beetle gets its name from the food they eat and what they live in—dung. Though this is quite strange, their behavior is even stranger. And so, researchers decided to study their behavior more in-depth.

A dung beetle will first locate a piece of dung. Using its back legs, the beetle will roll the dung towards its home location, while its head faces the ground. This is an example of homing behavior, where the beetle uses cues from its environment to navigate to a specific area. Baird et al. (2012) found that when the beetles did this, every now and again the beetle would stop, climb on top of the ball and circle around it in a "dance." Then the beetle would get back down and continue rolling the ball before doing this again. Eventually it became hypothesized the reason for this behavior was due to the beetle's ability to use celestial cues from the sky to efficiently roll the ball in a singular direction. This cue is the sun (Baird et al., 2012). Several researchers tested this hypothesis by changing the direction of the sunlight to see if the beetle changed its direction rolling the ball home (Baird et al., 2012; Dacke et al., 2003; Dacke 2014). The idea behind this was to understand if the beetle was reliant upon the sun rather than another cue to navigate. When the beetle was moved or the sun was moved, using filters or artificial light, the beetle always followed the direction of the sun. These experiments showed that this small beetle could see polarized light, and uses it to guide him and his dung ball home.

Insects have been studied intensely in their relationship to polarized light. For example, night flying moths, *Epiphyas postvittana* (Danthanarayana & Dashper 1986) were found to respond successfully to moonlight polarization of the sky in flight. Aquatic insects have been shown to be attracted to artificial objects that polarize light. One study found that surfaces of red and black cars attract the most polarotactic insects based upon the way light reflects and polarizes off of the car (Kriska et al., 2006). This represents a danger to aquatic insects who land on the roof of these cars mistaking it for water (similar polarization properties). Amphibians have been known to use polarized light cues to orient themselves. In an experiment with tadpoles (Aurburn et al., 1979), researchers found these organisms oriented themselves at sunrise and sunset in laboratory conditions when their arena was polarized. In the case of octopuses (Shashar & Cronin 1996), a study conducted a target-patterned choice experiment where trained octopuses had to make decisions between polarized cues presented to them. They found that octopuses were able to distinguish differences in polarized light patterns. The study concluded that their octopus could see polarized light, and the ability to see polarized light may be a behavioral mechanism to find prey or to communicate with other octopuses. It has also been shown that fish larvae of *Premnas biaculeatus,* who live in coral reefs, can detect polarization cues (Berenshtein et al., 2014). Using several experiments to test larvae responses to polarized light cues, they found that the direction the fish larvae swam was correspondent to the conditions of the sky. When a fully polarized sky was viewed, fish larvae were successfully able to orient themselves to the direction of the polarized cues. This behavior is quite distinct..

It has been suggested by several lab-experimental studies that birds can see polarization cues in the environment, and orient themselves on the basis of these signals. However, why birds use the signals of polarized light, and if they can detect these cues in the natural environment is relatively unknown. It has been theorized birds may use polarized cues to navigate, orient themselves and forage.

1.4 Birds and Polarized Light

1.4.1 *Early experiments*

In the early 1950s, several experiments were conducted to study bird orientation to polarized cues from the sun, and if the magnetic compass needed these cues to function (Hoffman 1954; Kramer 1952; Schmidt-Koenig 1958). Most earlier experiments' study species were starlings and pigeons. In 1952, Gustav Kramer designed several experimental approaches to understand how birds orient themselves in relation to the magnetic compass and the sun. He first captured starlings and put them in an aviary with large sums of iron to mimic the effects of a magnetic field. When this did not give him a result, he understood it was perhaps due to the need of the starlings to see the sky. He then designed a pavilion cage with six windows and two mirror positions. First, the starling would orient itself with the sky from the open windows. Then, the windows would be shut, and two mirrors would be placed in front of the artificial light from inside the pavilion. The windows were then opened, and the researchers recorded the new direction of the starling. This was done to measure the incident light and scattering coming from the mirrors, which were shifted to different degrees of orientation to mark the bird's orientation to the sun. Kramer (1952) then used a similar method, but without a cage. He placed twelve feeders around a starling and allowed the bird to choose a feeder based on the incident light coming from the mirror. Throughout this experiment, it was shown that the starlings changed their orientation to match where the light was coming from similar to mapping the sun across the sky as a compass. But when there is no sun (such as a cloudy day) orientation is not shown.

A similar idea was conducted with homing pigeons that were trained and released over 200 miles. Though there was no clear result of the behavior, Kramer (1952) hypothesized that pigeons too used the sun to navigate. Other German scientists found a similar observations (Hoffman 1954; Schmidt-Koenig 1958). However, this finding that birds may be able to detect polarization cues was just in its beginnings in the 1950s, and is still being experimentally tested today.

1.4.2 *Modern experiments*

Later experiments continued testing bird polarization detection through the usage of similar orientation of hexagonal, circular or octagonal cage experiments where the design of the experiment differed slightly between each study (Able 1982; Helbig et al., 2010; Moore 1986; Moore & Phillips 1988; Philips & Moore 1992; Wiltschko et al., 1972). In these studies, migratory birds were given a food cue, and located this food using the magnetic compass directions and a light source, such that it was theorized that the magnetic compass might be primarily mediated by polarized light. These birds were trained to use the cages, and experiments were conducted mostly in a laboratory setting.

Several studies revealed that birds may be sensitive to polarized light, and use polarized light patterns of the sky to orient themselves, and to calibrate their sun compass, similar to earlier studies of aforementioned German scientists. Such studies have suggested that birds such as Yellow-rumped warblers (Moore & Phillips 1988; Philips & Moore 1992), Zebra finches (Muheim & Pinzon-Rodriguez et al., 2017), Blackpoll warblers (Able 1977), Northern waterthrushes (Moore 1986), Kentucky warblers (Moore 1986), White-throated sparrows (Able 1982), blackcaps (Helbig 1989), chickadees (Duff et al., 1998), Clark's nutcrackers (Wiltschko et al., 1999), jays (Duff et al., 1998; Wiltschko et al., 1999) and homing pigeons (Chappell & Guilford 1995; Kramer 1952; Muheim 2011) are able to detect polarized light in the visible range. A different method than that of the hexagonal or circular cage study, is a "cross-like" maze that mimics a magnetic compass. In this study by Muheim & Pinzon-Rodriguez (2016) Zebra finches, a central Australian bird, were trained to locate "hidden food" within the maze. Through the use of an overhead polarized light, birds were only able to orient themselves when this was on, suggesting that Zebra finches' magnetic compass can only work when polarization cues are given. This means that they are sensitive to polarization patterns.

In addition, studies have shown birds use polarized light patterns to calibrate their sun compass *specifically* at sunrise and sunset rather than throughout the day. In Moore (1986), species such as the Ovenbird, Northern waterthrush, Kentucky warbler, and Hooded warbler were used in cage experiments at these earlier and later times of the day. At these times, the sun is positioned in a way to provide direct information of compass direction, which makes it easier for birds to adjust themselves accordingly to the rising and setting sun that is horizontally positioned (Moore 1986; Muheim et al., 2011). It was found that these birds used the sun to direct themselves, and could furthermore suggest that birds could use such cues in migration. In this way, it has been suggested that many migratory birds take their long flights early mornings or at dusk as polarization cues are more direct.

On more overcast days, some have argued that the polarized light pattern is strong despite less direct exposure of the sun, and night polarization from the moon acts just as strongly as daytime polarization (Horváth et al., 2014). However, many studies point to the fact that on overcast days, birds do not orient themselves as well as they would on clearer days. One study who looked at nocturnal migrants off of New England, notes that factors such as wind and bird "restlessness" (Able 1977) may impede on a bird's ability to orient and navigate themselves. This may be because detection and use of magnetic field relies on detection of polarizes cues. However, this has not been proven.

To argue with bird-polarization research, Muheim et al. (2011) states that there is little evidence to show that birds use the sun as a compass for orientation, rather birds may use cues from their environment specifically at sunset and sunrise for seasonal and latitudinal compass information. Furthermore, Martin (1999) states that even though there is evidence of polarization in some birds, Martin (1999) doubts that polarization can be perceived directly by birds, arguing that there could be another component to polarized light. The argument points several weaknesses in the theory such as polarized sensitivity in birds. This is specifically because it is not known if birds can really "see" polarized light based on the avian retina, or if they sense other factors that may look to researchers like it is polarization-mediated, but they are using other signals instead.

If birds are sensitive to sensitive to polarized light, the behavioral mechanisms for seeing polarized light are rather theorized than known. As implicated before, birds could use skylight polarization patterns to migrate, to orient, and even, to find food (perhaps using water-based cues). This beforehand research shows that this is unknown.

However, in a recent unpublished study conducted by Robertson et al. (2021, *in prep.*), researchers found that wild songbirds (as in untrained birds) can see horizontally polarized light and use it to locate bodies of water through the usage of choice experiments. This has never been done previously, as most experiments used trained birds, and carried out their studies in the laboratory. This study used three experimental trials. The first trial was using hand-made feeders with an acrylic base of five different colors. These colors, ranging from white-shiny to black-matte, allowed researchers to understand if birds can see polarized light when given a range of different color feeders. They saw how birds made food selection choices when given different polarization patterns, and choosing one feeder over the others based on its patterns. The second trial used ground panels of four different colors to simulate the effects of water polarization patterns on the ground. Researchers observed how birds interacted with one treatment over the other based on its polarization differences. The final experiment used different color and texture heated bird baths to understand how a bird makes the choice of going to polarized bath or a nonpolarized bath. Though there was no preference in experiment two, experiment one and three showed that songbirds do make a choice to visit a polarized feeder and bath over a depolarized feeder and bath. This novel finding suggests that birds may be able to detect polarization cues of water in visible and/or ultraviolet range when given a series of food-based choices. This experiment sets the premise for my field-based choice experimentation.

1.4.3 *The avian eye*

It is not known how the avian retina, consisting of double cones, may be able to perceive polarized light. In insects, researchers have found evidence of insect organism's capability to perceive polarized light. Insects have what is called a Dorsal Rim Area or DRA, which essentially allows these organisms to detect polarized light when they look up at the sky

(Danthanarayana & Dashper 1986). It is theorized that birds have similar photoreceptors to insects to detect polarized light even in the ultraviolet range (Bennett & Cuthill 1994; Hart & Vorobyevas 2005; Young & Martin 1984). These are called cryptochromes, which are also involved in magnetoreception (Muheim 2011). This means that the light-dependent magnetic compass receptors and the polarized light receptors could work in a similar fashion. Essentially, colors trigger chemical reactions. When something is polarized, it is vibrating up and down or left and right (vertical and horizontal, respectively). The combination of this allows animals to see polarization. However in birds, this is much more complex: shorter wavelengths dictate direction and longer wavelengths dictate disorientation (Muheim 2011). What has been shown, according to Hart et al. (2005), is that birds can detect light in the ultraviolet range (300-400 nm) and the visual range (400-700nm), but this is not to be confused with *polarized* light. Furthermore bird's ability to see "color" depends on several factors such as oil droplets, and are able to discriminate and categorize color compared to backgrounds (Kelber, 2019). But how they can is evolutionarily and ecologically undecided. This means that it can be possible for them to "see" polarized light and use this as a cue to navigate, to orient and to find food or other resources, like water.

1.5 Ecological Traps and Polarized Light Pollution

There are both natural sources of polarized light and anthropogenic, or human created, sources of polarized light. Light from the sun and light from the moon represent the major natural light sources (Horváth et al., 2009). When light enters the atmosphere, it is generally unpolarized. When in contact with gases in the atmosphere, part of that light becomes partially polarized (Horváth et al., 2009).

When natural light is scattered and reflected off of surfaces such as water bodies or surfaces like rocks and soils, it can be partially or fully linearly polarized. Water is the only natural known polarizer of light that has been studied thus far. As stated before, water polarizes light through reflection when light bounces off smooth water surfaces, and absorption when light is taken in by a lake bed or refracted by particles. Horváth et al. (2014) states that depth, turbidity, transparency, color, surface roughness, and composition below the water influence reflection and absorption polarizing characteristics of water.

Artificial, or anthropogenic, sources of polarized light includes any light source such as a light bulb, that mimics the properties of the sun or the moon. Anthropogenic sources of polarized light represent a subsection of pollution called 'ecological light pollution' or 'polarized light pollution.' Most of this research has been on understanding how artificial sources of light such as human infrastructure, can disrupt animal behavior, survival, and reproduction (Horváth et al. 2014). For example, a solar panel grid that is horizontal to the ground, is an object that is both dark in color and smooth in texture, and is known to polarize light (Horváth et al., 2014).

A bird flying above the solar panel reaches the Brewster's angle, where there is complete or perfect polarization, and suddenly sees the solar panel on the ground below. The bird may mistake the solar panel for water as its cues are similar to the polarization cues of water, and fly down from the sky only to meet its doom. By the time a bird may realize it is not water, it may be too late for the bird to stop its dive from the sky and fly away. Collisions severely injure birds, or kill them. Kosciuch et al. (2020) found that water-obligate birds were landing on solar panels 90% of the time at their study site. Similar studies report similar findings on bird collision mortalities rates, but are much lower in estimates (Visser et al., 2019; Walston et al., 2016).

Compared to natural sources of polarized light, artificial sources of polarized light are a threat to the survival of birds whose health is deteriorated by their attraction. These collisions to anthropogenic sources of polarized light are mostly with water-associated birds who search for water from the sky. Several studies have suggested that artificial light from infrastructure, such as buildings, disrupts bird activity as their attraction steers birds away from migratory patterns and towards artificial objects (Lao et al., 2020; McLaren et al., 2018; Winger et al., 2019; Zhao et al., 2020). Water-obligate birds, such as Brown pelicans, have collided with roads or parking lots due to this object's ability to mimic similar cues of water (Kriska et al. 2008).

These scenarios are what is known as an ecological trap. Horváth et al. (2010) defines an ecological trap as a low quality habitat that animals choose to settle in, unaware of the consequences settlement may impose upon survival. Human infrastructure, industries and agricultural technologies have furthered polarized light pollution for the worse, allowing animals to make poor, but accidental decisions based upon a similar, but artificial landscapes. Horváth et al. (2009) lists black plastic sheets, asphalt roads, cars, oil spills and open-air waste oil reservoirs, dark-colored paintwork, glass panes, and even black gravestones as anthropogenic sources of polarized light.

There have been many documented instances where birds' survival is threatened by their submergence in oil waste pits (Esmoil & Anderson, 1995; Flickinger and Bunck, 1987; King & LeFever, 1979). This endangers the health of the bird swimming, but also hinders their ability to fly as feathers when wet are heavy, and prevent the bird from leaping into the air and soaring off in the sky. Horváth et al. (2014) showed that open air oil pits polarize light, and so, birds could believe this to be water from their place in the sky as polarization cues from the dark body of oil could be similar to those of natural water.

Horváth et al. (2014) also found that windows polarize light, using a polarized light camera that could measure the degree and angle of polarization of the windows. In this study, insects that were found to be attracted to artificial sources of polarized light, attracted White wagtails, House sparrows, Great tits and European magpies to windows and a tarp that also polarized light. It was hypothesized that birds thought such polarized light objects were visually conspicuous as their behavior was noted (i.e. running around on the tarp and looking up vertically at building windows). However, it is unclear if birds see polarization of artificial objects and use it to guide them to food, or if they see insects first and the building just so happens to be polarized.

1.6 Management

The Migratory Bird Treaty Act (MBTA), created in 1918, forbids the hunting, killing, capturing, possession sale, transportation, and exportation of birds, as well as their feathers, eggs and nests. Essentially, the federal government fines companies for accidental bird deaths, such as a bird ending up in an oil waste pit, but also those electrocuted on powerlines or near industrial smokestacks. Over a thousand birds are protected under this treaty, though not *all* birds are protected.

However, during the Trump Administration, the MBTA was essentially derailed, allowing companies to continue “business as usual” as long as bird deaths were not intentional. This means that companies were not fined or found liable if bird deaths were accidental. This move angered conservationists. Under Biden, the MBTA is once again in place, but there is still work to do to conserve bird species interactions with human infrastructure.

To manage polarization effects in the environment, Horváth et al. (2014) suggested that people should stop driving red or black cars and start driving more grey-toned vehicles to halt the number of insects being attracted to such colors. Horváth et al. (2014) also mentions considerations to limit the effects of polarized light pollution for urban planners and other engineers. Among these are making surfaces rough to depolarize, making a grid-like pattern on the solar panel cell, making surfaces whiter to depolarize, and avoiding shiny objects in construction and product.

Horváth et al. (2010) and Fritz et al., (2020) show that different types of solar panel designs attract different abundances of insects. When there is a white border or white lines on the solar panels, less insects visit the cell (Horváth et al., 2010). Fritz et al. (2020) concluded similarly that bioreplicating the microtexture of rose petals on solar panels decreased the attractiveness of insects. Although this study was conducted with insects, it represents a potential new avenue of photovoltaic design to reduce the pollution of polarized light.

Though an undertaking to mitigate the infrastructure in the human environment, it is possible that animals like birds could detect polarized light, and may be using this signal for guiding their foraging behavior, and even migration. As more studies are released on this interaction, urban planners and developers may begin to ruminate how best to implement design in the built environment that does not distract the natural world. Companies and industries could build structures that decrease polarization, and in doing so, reinvent the city-scape. This would essentially lessen the ecological traps in the built environment, creating a safer place for animals to live.

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~INTERMISSION~

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I will now diverge from technical, scientific writing to accomplish a short, creative piece that aims to bridge the gap between the scientific research community and the non-scientific community. To do this, I will mimic the styles of Victorian to mid 1900s field guides to write a "testimony of the birds" based on my bird-related observations around one site. While doing this, I will use my human-biased experiences to understand the behaviors of these ecologically fascinating and significant creatures. The naturalist field is on the brink of extinction: learning identification skills and studying the anatomy of animals such as birds is often thought to be subpar to the thereafter research counterpart. This is my attempt for a revival of curiosity in nature writing that is less technical, but still provokes the same concepts. For my inspiration, I read sections of historical field guides and antiqued bird books that documented the conversational interactions of what birding used to be like.[3]

Bird writing was popularized in the Victorian age (late 1800s) by women who found a place in a repressive society encouraged by modesty, and discouraged voice. In a time where women were adorned with feathered hats, some protested against the plume trade. Naturalist writers such as Neltje Blanchan, Merriam Bailey, Lucy Warner Maynard, Harriet Hemenway, and Olive Thorne Miller (Harriet Mann Miller) broke from societal norms to write romantically

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[3] Books investigated for inspiration: Bent, Arthur Cleveland. *Life histories of North American flycatchers, larks, swallows, and their allies*. Vol. 179. Courier Corporation, 1963; Bent, Arthur Cleveland. *Life histories of North American jays, crows, and titmice*. Dover Publications, 1964; Blanchan, Neltje (Selected from the writings of and Preface by). *Birds*; The Nature Library. Doubleday, Page & Co. for Nelson Doubleday, 1930; Flagg, Wilson. *A year with birds; or The birds and seasons of New England*. Boston, Estates and Lauriat, 1881; Stearns, Winfrid Alden. *New England bird life: being a manual of New England Ornithology*. Boston, Lee and Shepard, 1885; Warren, Benjamin Harry. *Report on the birds of Pennsylvania. With special reference to the food-habits, based on over four thousand stomach examinations.* E.K. Meyers, 1890.

about birds different than academia. These works were creative, conversational, observational, conservational, and beatific. Unlike male ornithologists or naturalists, women did not have the chance or the opportunity to take part in leadership roles, but this did not lessen their love for birds. Their written works were as much important as the written works by their male counterparts; they found similar observations, just written in a different way. The work that such women did helped to pass the 1918 MBTA to ensure the health and safety of birds. Without such a movement from these Victorian women, such a crucial treaty act that is still important today, would have never been enacted.

1.7 A Testimony to Birds

Listen to the following as you are reading:
~"Стародавній Танець"/ "Чумацький Шлях" from *Songs of Grief and Solitude,* Drudkh~

The 3 o'clock sun settled off behind the blue-tainted mountains as the winter breeze stunned the last living plants still mourning for the summer's heat. I sat on a rock near my site, and saw the sun gratify the sky with oranges and reds I never did see around the Great Lakes. My mountain across the Hudson seemed to shrink in its essence as this occurred, and the yellow plants in the near garden shriveled to greys and browns as it sat in front of an intimate, Victorian, palace. During this scenery, the birds before me rattled the forest with small hands, and I watched as a dear Black-capped chickadee fell from the feeder with a sudden drift he did not prepare for. I smiled at this, and decided to take my equipment home for the day.

In the early spring of this year, I found myself in a decrepit forest not too far from my site. I was learning about something rather unkind and peculiar—unnoteworthy to the topic at hand—when I caught my shoe around a branch tangled between the snow. I did not fall, but I placed my hands out before me to stop myself from doing so. My hands unfortunately embraced a stream of sap oozing from a Silver maple, half solid at the ends of its fingers near the soils. A bulge of fresh sap coated a slight crevice in the bark. My left pinky was swallowed by this, as the rest of my fingers were drowning in the torpidness of the sap-fall. I felt a slight kiss from the stream onto my own fingers as I tried lifting them away from the sap bark. The forest seemed to dull in that moment, and I began to feel unease as the sun begged for my goodbyes. The whispers of foraging creatures hid in the shadows watching me. I noticed this, and escaped the tree for only a moment in desperate need of solitude. This was before my eyes caught the sap stream's gaze in the deafening sunlight of what appeared to be a reminder of a summer sunset behind the mountains. This sun provided forest figures with intricate tonalities. Sap eyes examined me as I examined them. The enthralling substance originated somewhere beneath the winter bark, but this was invisible to me. The sap's shine made this particular tree stand on its toes in a land of white flooring and spineless branches. It was there I wondered about such a thing—mystical and brilliantly radiant.

A Red-bellied woodpecker appeared suddenly at the side of this tree, and I cautiously moved away from the sap-fall into deeper snow, until my heel hit another forest entanglement. I watched this bird's barred feathers twitch from a slight breeze, as its reddened head moved erratically around him. It seemed to have understood something about the forest that I could not comprehend. As he moved slightly towards the still sap-fall, the bird produced a series of shrills, before he began pecking at the sap before him. Unnaturally invested in this sight, I was soon swallowed to the stomach of the naked forest that encompassed me, and reached a similar rhythm of the species around me. Several songbirds rested on a tree above my head: a Tufted titmouse, a Dark-eyed junco to my right, and a White-breasted nuthatch, whose nasally voice was overpowered by the woodpecker visitor. Although these small songbirds did not greet the lone woodpecker, they viewed the tree and its visitor for a long while as the sun gracefully blessed the sap's shine. When the woodpecker flew off, quite unfashionably, the nuthatch jumped to the bark of the tree, and pranced around the sap-fall, before it too flew far away in a grey movement. The titmouse and junco only hovered close to the conspicuous tree. They disappeared before I could manage to speak a word.

This dubious encounter in the forest provoked within me a child's fascination. This thereby plagued my thoughts as I traveled back to my lone site for the following weeks. I wondered if this invitation I received that one evening upon sunset from the sap-fall was observational evidence of my own experimentation with artificial elements, or was this, rather, a familiar scenario outside the realm of where my thoughts were directed. After several weeks in the beckoning forest, I did not see a similar interaction with something so natural, though I did with my artificial elements. Perhaps no creature of humankind was meant to intrude upon birds' sun-secret, and since I had betrayed a bird-human boundary, it was never meant to be seen again in the shine of the sap-fall.

During my placement on the rock at my site, I documented several occurrences: songbirds are inquisitive creatures, they enjoy the morning sunshine, they can be quite noisy in the presence of visitors, and they seem to like shiny objects. Though I cannot answer why to any of these observations with certainty, I conjecture, based off of previous readings in my study, that such birds may like shiny objects because they provide a nutritional basis. This may be related to the positioning of the sun, where bright sunlight enhances an otherwise dull tree in an aching forest. With my observations, though no solid reasonings at the moment, my site seemed quite similar to the observance I had weeks before.

As I neared the end of my experiment, rain melted away the snow, and the sun frequently rose in the sky. I was greeted by green once more, and my rock became covered in such, looking quite brittle to the touch. My songbird friends—Downy woodpeckers, Blue jays, Yellow-bellied sapsuckers and others—depressed the silence at my site with soft talks and a gust of excitement in feathered displays. Interconnection existed here, though a full cognition was obscured by the detailed factors that muddied my simple interpretation. Each bird exhibited a type of behavior in foraging, in conversations, and in movements related to the rising and setting of the mountain sun. I wondered if their eyes perceived the land similarly as I, or if their eyes, small upon their soft heads, could peer great depths into a place that I will never, or have yet to, grasp an awareness upon.

A warmth of spring arousal enticed the birds and their prey, and the prey's prey. The grass began to reach up past the rock I sat upon, while the twisting trees hovered over and procured safe habitats for the earthly, unwashed creatures. The sounds of the forest thickets mimicked those across the lawn of the Victorian palace. This transmitted uncharacterized, yet beatific, sounds to the water of the Hudson to where the birds flew down from the sky to bathe. The arthropods crawled under my toes as I stood to leave, and a chickadee came down from a tree to scurry them away.

As I left the forest community with my equipment, I saw a conifer with a similar stream of sap to which the sun hit precisely. I pondered if something similar was to be unveiled to another passerby in the shrouded and placid coterie of feathered creatures.

2 Introduction

Animals use signals or cues from the environment to make choices that best suit their survivability (Robertson & Hutto 2006). One way animals use these cues is for finding food. A phenomenon known as polarized light has been studied as an explanation to how animals navigate a multifaceted environment. Polarization occurs when waves are constricted to a singular direction. Sunlight, an example of a wave, is the natural source of all polarization on Earth. It consists of electromagnetic rays vibrating without directionality within the plane of vibration (Können 1985). Sunlight is generally unpolarized when it reaches the atmosphere. Once it interacts with particulates in the atmosphere, such as water or gases, the light reflects and refracts becoming polarized to a viewer's eye (Cronin et al., 2011). According to the Rule of Umov (1905), darker and smoother objects have a greater degree of linear polarization. Objects that are light, matte, and have an uneven texture are strong depolarizers of light (Horváth et al., 2014). Thus, color and texture are important in determining an object's ability to polarize light. There are both natural and artificial objects that polarize light. Water is the only natural body known to polarize light that has been studied thus far. The surface of the water reflects sunlight. The darker the water body, based on the water's turbidity as well as the texture and color of the lake bed, the more light that will be absorbed, and thus, a higher degree of light will be polarized (Horváth & Varjü, 2004). The net combination of reflection and absorption processes result in polarization of sunlight to an observer's eye up to 100% the darker and more turbid the lake bed. Tree sap may be another natural polarizer given properties similar to water, but this has not yet been uncovered. However, sap simulations have been conducted (Horváth et al., 2019). The study of polarized light is crucial as it could provide an explanation to how animals navigate, using cues from their environment, to guide their foraging behavior.

Studies have suggested a great taxonomic diversity of animals who can detect polarized light cues: butterflies (Reppert et al., 2004; Sauman et al., 2005; Sweeny et al., 2003), ants (Narendra 2007; Vowles 1953; Zeil et al., 2014), octopus (Shashar & Cronin 1996), frogs and frog larvae (Auburn et al., 1979; Justis & Taylor 1976; Phillips et al., 2010), crickets (Brunner & Labhart 1987; Heinze 2014; Labhart 1999), cockchafers (Hegedüs et al., 2006), fish (Berenshtein et al., 2014; Flamarique et al., 2001), newts (Landreth & Ferguson 1967), and various insects (Black & Robertson 2019; Danthanarayana & Dashper 1986; Heinze 2017; Horváth 2010; Kriska 1998; Kriska et al., 2006; Mathejczyk et al., 2019; Weir & Dickinson 2012). Tadpoles were found to orient themselves to the sun specifically at sunrise and sunset when they were given polarized light cues in a laboratory experiment (Auburn et al., 1979). A study with octopuses (Shashar & Cronin 1996) found that these animals could differentiate between polarized light patterns given by the researchers. They conjecture that seeing polarized light may be a behavioral mechanism designed for the octopuses to communicate with other octopuses or to find food. It has been experimentally shown that aquatic insects were more so attracted to cars that had black and red paint rather than cars that were lighter in color, and these paint colors polarized light. This suggests that some insects may be capable of seeing polarized cues from the built environment that mimic the cues of water (Kriska et al., 2006).

Birds have been experimentally shown to orient themselves to the polarized light patterns of the sky. These experiments were conducted in cages where past researchers were able to manipulate the polarized light cues of the environment sometimes using a food source to guide birds through the cage (Able 1982; Helbig et al., 2010; Hoffman 1954; Kramer 1952; Kramer 1959; Moore 1986; Moore & Phillips 1988; Philips & Moore 1992; Schmidt-Koenig 1958; Wiltschko et al., 1972). The following birds, but is not limited to this list, have been studied and shown to discern polarized light cues: Yellow-rumped warblers (Moore & Phillips 1988; Philips & Moore 1992), Zebra finches (Pinzon-Rodriguez et al., 2017), Blackpoll warblers (Able 1977), Northern waterthrushes (Moore 1986), Kentucky warblers (Moore 1986), White-throated sparrow (Able 1982), blackcaps (Helbig 1989), chickadees (Duff et al., 1998), Clark's nutcrackers (Wiltschko et al., 1999), jays (Duff et al., 1998; Wiltschko et al., 1999) and homing pigeons (Chappell & Guilford 1995; Kramer 1952; Muheim 2011). There has only been one study thus far that experimentally shows that wild songbirds are able to detect polarized light when given a food-associated cue and choices between a polarized and non-polarized signal (Robertson et al., 2021, *in prep.*). Most of what is known about polarized light and animal vision exists in the horizontal plane. This means that no one yet has experimentally tested or suggested if wild or untrained birds are sensitive to vertically polarized light. It has been theorized that birds could likely already see horizontally polarized light of water (Horváth et al., 2014). If this is true, birds should be pre-adapted to see vertically polarized light as this would require birds to simply tilt their heads 90 degrees to see water vertically. It is also unknown why birds, if detection is true, see polarize light, and what they use their vision for.

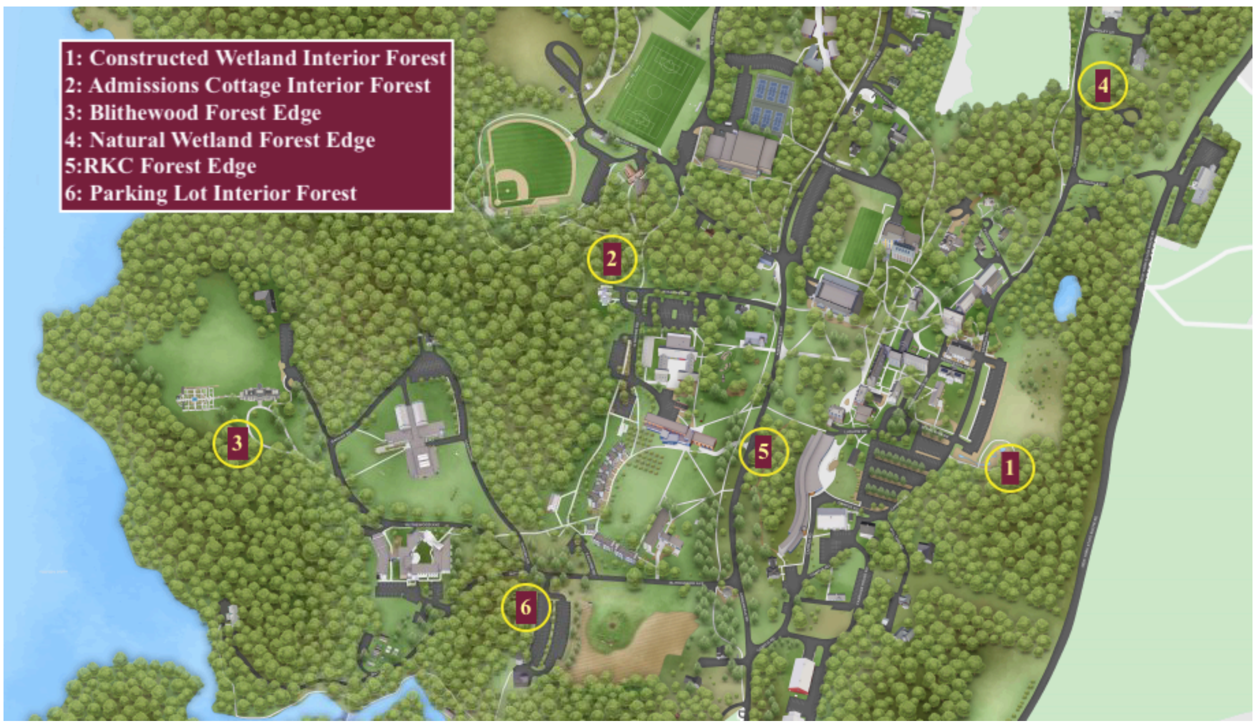
Artificial or anthropogenic sources of polarized light can include glass panes, black plastic sheets, asphalt roads, solar panels, oil spills and cars (Horváth et al., 2010). These objects are similar in its visual properties: they are smooth and dark in color. Both of these properties contribute to a high degree of polarization. This known as polarized light pollution, where man-made objects can intrude upon the behavior of an animal. Artificial light from infrastructure has caused disruptions for migratory birds (Lao et al., 2020; Zhao et al., 2020). Water-obligate birds have collided with parking lots (Kriska et al., 2008) and solar panels (Kosiuch et al., 2020) most likely mistaking anthropogenic materials for water given similar polarized light properties. Thus, investigating if birds in the wild can see polarized light cues, and understanding how they use these cues, provides considerable insight into potential problematic situations for animals when they interact with the built environments. This suggests a future avenue for urban developers and environmental managers where they begin to investigate polarization properties of cities and towns to make decisions on how best to implement depolarized infrastructure in order to dissuade animals from an interaction with artificial objects.

My study addresses two questions: (1) Can birds see vertically polarized light when given a food-associated cue, and a choice between two treatments, one that polarizes light and one that is non-polarized?; and (2) Is natural Maple tree sap polarized? I designed an experiment furthering the findings of Horváth et al. (2019), and previous studies who examined avian behavioral responses to polarized light cues. I predicted that if I attract birds to a treatment suet feeder that is associated with a vertically polarized and conspicuous treatment wrapped around one tree, and a treatment suet feeder that is associated with a vertically unpolarized treatment wrapped the second tree, with both trees similar in size and in close proximity distance, then I should see more bird visits to the suet feeder with the polarized light treatment as they make a choice over the non-polarized feeder which is controlled similarly outside of the treatments. I used camera operators to monitor bird visits to the suet feeders for both treatments. A baseline study was done before treatments were added so as to see how visits changed when treatments were added into the experiment, and to see if birds prefer one tree over the other. Bias was further controlled by switching the treatments from one tree to the other. Statistical analyses of ANOVAs, Mixed Models, and Generalized Linear Mixed Models were conducted to understand the effect of explanatory variables and species on treatment visitations. More bird visits to the treatment associated with polarized light signaled polarization detection. To test if tree sap and

Maple syrup are polarized, I imaged the polarization properties of tree sap and syrup on four different types of wood found in nature when natural sap was painted over the bark. I made conclusions about avian foraging behavior based on their ability or inability to see vertically polarized light. I connected these conclusions with the effectiveness of my treatments compared to sap polarization properties.

3 Methods

3.1 *Study sites*



I conducted a field experiment at multiple sites on Bard College's campus in Annandale-on-Hudson, New York, USA. The study was conducted at six sites total for three weeks (Week 1: Baseline, Week 2: Treatment One and Week 3: Treatment Two). The first experimental trial was held in the fall from late November to mid-December of 2020. The second experimental trial was held in the spring from early March to late March of 2021. Treatments and cameras were placed in habitats of relatively undisturbed forests, near a wetland habitat, and forest edge habitats. All sites were reasonably removed from campus activity.

3.2 *Vinyl and Polarization Camera Technology*

The Rule of Umov (1905) states that smooth and dark surfaces are the best polarizers of light. Manipulating both the texture of a plastic surface (shiny or matte), and the color of that surface gave me a better understanding in if birds see and respond to vertically polarized light using visual cues in a choice experiment.

Six foot-length rectangles were cut out of clear 20 Gauge 54 inch vinyl found Joann's Fabrics. All six were painted with acrylic matte Black 3.0, advertised as the blackest paint in the world from Culture Hustle, USA. Three coats were painted on one side, and left to dry. The side painted on dries as a matte surface, and acts as a strong depolarizer. The side of the vinyl that is shiny, with the black coating seen through the clear plastic, acts as a strong polarizer. These properties of the shiny surface—smooth and dark—exhibit strong polarization of reflected light (Horváth et al., 2009)

I imaged these treatments in the visible range of light and the ultraviolet range of light using two modified and specialized cameras designed to capture the reflected polarized light coming from the polarized and depolarized side. A Canon DSLR camera with a polarization filter had been fashioned into an imaging polarimeter to see polarized light only in the visible spectrum. A Nikon DSLR modified camera with a crystalized lens was used to measure polarized light only in the ultraviolet range. Treatments were laid flat on a grey-black pavement for images. Each camera was put on a tripod and were positioned to the known Brewster's angle of water (56 degrees), or the angle at which most polarization occurs, through the use of an attached protractor to the edge of the camera. Once the camera was in focus to the treatment, and the exposure was set correctly, the polarization filter was rotated three times which represents three different angles. This determines the exact angle and degree of polarized light by subtracting the angles in which the filter was rotated to the brightness of pixels. Essentially, it represents red, green and blue colors according to the way the photons are vibrating in relation to the angle of polarization. In the ultraviolet (UV) range, this intensity is a pinkish-purple.

Treatments were placed in three different ways to maximize different polarization of light: away from the sun, towards the sun, and sky polarization (UV). The images were then imported into AlgoNet® where polarized light in the visible and ultraviolet are seen by the treatments visually, and statistical analysis was conducted to determine the effectiveness of the treatment's polarization. This was done creating a filter on a section of the object that would measure the polarization of that section. This software is designed through the use of visual algorithms built from modules made to tackle the visual aspects of sky polarization when the sun is present in the sky. It computes the intensity, degree, and angle of polarization of the treatments.

3.3 *Experiment Specifications*

3.3.1 Tree Sites

Two trees (<40dbh, ±10dbh) located <5 feet of each other were chosen (Figure S1) at each site. These trees were in the following habitats: interior forest (Figure S1 a-b, f), forest edge (Figure S1 c, e), and near wetland (Figure S1 d). Trees were determined by hiking through habitats to locate two trees who had similar dbh measurements, and were close in proximity.

3.3.2 Food Cue

Cotton string was tied around both trees at breast height and knotted at the back of the tree. Identical 5 inch by 5 inch black, caged, suet feeders were hung on the approximate North side (determined by a compass) of both trees to allow the least amount of sunlight to blind the cameras. C&S Hot Pepper Delight No Melt suet dough was placed in both suet cages on the trees. This food cue was chosen as it is advertised to keep away squirrels.

Feeders were monitored every other day or every day, and suet cakes were replaced when they were 30% consumed or if suet dough was significantly different in size from the other. If this was the case, pieces of the dough were broken off until the dough matched the dough on the other tree. If there was only 20% left of the dough, a new dough was placed into each cage. This was done to avoid any further bias in the experiment. If there was more dough on tree position A than tree position B, birds might visit position A more just because it had more food.

3.3.3 Motion-Cameras

Two motion controlled cameras, Raptor Surveillance Camera/Trail Camera by SECACAM, were placed 10 feet from each tree in the fall, and in the spring, were placed at 6 feet from each tree to give a close-up of the tree. These cameras are specifically designed to capture the quick movements of birds, and were thus used to monitor bird visits to each suet feeder and treatment over time. The cameras were set to two captures per event, with a high resolution, and no SD card overwrite once the images filled on the SD card. Cameras were monitored each other day or every day to check on battery power and SD fullness. If the SD card was about to be filled (less than 200 captures per event left), SD cards were taken out of both cameras even if the other camera had more shots. This was done to keep each camera a control for the experiment.

Cameras were mounted on 3 feet 14-Gauge Steel U-Fence posts from Home Depot and Amazon with an attached 6-inch by 2-inch rectangular wooden block. Two holes were drilled into the blocks, at the top and bottom. Zip ties were strung and secured through these holes and the holes on the fence posts. The back of the cameras were strapped onto the wood block attachment. The posts were then pushed into the ground at a slight angle to face up towards the location of the feeders and treatments on the approximate North side of the tree.

3.4 *Experimental Trials*

3.4.1 Baseline

A baseline study was conducted before the experimental treatments to see if birds had a preference or bias to one tree over another. The baseline also offers insight into how conspicuous treatments are by comparing bird visitations before and after treatments were added into the system.

In the baseline trial, no treatments were placed on the tree. Only suet feeders hung at breast height. Tree position A was always the left tree, and tree position B was always the right tree at every site. This positionality was recorded and is important when referencing the treatments. Cameras monitored the baseline study from five days to a week depending on each site. The same experiment specifications were used for the baseline as the experimental trials, outlined in section 3.3.

3.4.2 Fall 2020: Experiment Trial 1

After the baseline trial was over, the treatments (described in the above section) were added to each tree to understand avian attractiveness to vertically polarized light. During experimental trial 1, across all sites (1-3), the shiny, polarized treatment was secured to tree position A, whereas the matte, depolarizing treatment was secured to tree position B. These treatments were essentially wrapped around the trunk of the tree above the suet dough and secured using two large alligator clips, one at the top and one at the bottom. This was snug, and flat around the tree. Experiment 1 was designed for one week. The same experiment specifications, outlined in section 3.3, were used.

3.4.3 Spring 2021: Experimental Trial 2

After experimental trial 1 was finished, the treatments were switched. This was done to avoid bias. For example, if there was a nice berry bush or a small shrub next to tree position B, birds might be biased to go to that tree. This does not rely on the specifications of the study, but rather a bias that exist outside of the study that cannot be controlled.

The matte, depolarizing treatment was secured to tree position A whereas the shiny, polarizing treatment was secured to tree position B. They were again wrapped around the trunk of the tree directly above the suet dough and fastened with two alligator clips. Experiment 2 was also designed for one week. The same experiment specifications, outlined in section 3.3, were used.

3.5 *Statistical Analysis*

3.5.1 Image-Counting and Rules

Images from the SD card were downloaded to an external hard drive. Bird visits were counted over time. To do this, visits were counted within the same time frame at tree position A and tree position B to lessen bias. The numbers were tallied in an excel spreadsheet which included: location of the site, location number (1-3, 4-6), position (A or B), treatment (BL-baseline; M-matte; S-shiny), and species of birds, under which tallies were put in columns. Birds were identified by their species and recorded as such.

Each image captured in the fall of this study were looked at across sunrise to sunset, for a total of about 80,000 images investigated. These were counted in January of 2021 for a duration of three weeks. Due to the length of time counting occurred, the images captured in the spring of this study were limited to 6am to 10am, and 5pm to 7pm. It has been suggested that sunrise and sunset times are when birds are most active, and can more efficiently conceptualize polarization cues from the sky (Moore 1986; Muheim et al., 2011). This lessened image reviews to about 30,000 images.

There were four rules and considerations for including or excluding a bird count in image reviews: 1. The bird must be interacting with either the treatment or the suet feeder such as it being directly on the treatment, or eating from or positioned on the suet feeder. A bird did not count if it was flying near the tree, if the bird was on the ground, or if the bird was anywhere else on the tree such as the upper or lower trunk; 2. When questioning if a bird is a new visitor versus the same visitor, the time of the images from one image capture to the next were investigated. The same species of bird reappearing throughout multiple images in a similar place, only counted as one bird count. A five-minute rule was applied. For example, a Blue jay showed at the suet feeder at 10 am. Five minutes passed, and other bird species visit the feeder. A Blue jay then appeared at 10:05 am. This would have counted as two different Blue jays. But, if a Blue jay showed up continuously between 10 and 10:05, this would have only counted as one; 3. A bird may stay on the treatment/feeder for one image or multiple images and they would have still counted as one bird; 4. For any weather events that obscured camera clearness, or caused dissimilarities between the treatments, images were not counted until the cameras could visualize properly, and the treatments were well-distinguished. During rain or snow, the matte treatment often looked shiny as the paint was not water-repellent and so, it would become wet. Due to this, birds were not counted as there was not a difference in treatments. Similarly, when there was early morning fog, snow, rain events, or even extremely bright sunlight, the cameras appeared blurry. Since a clear picture was not painted, birds were not counted during these time frames for both positions.

3.5.2 Data Analysis

Several ANOVAs were computed in R (v.1.3.1073) for both the fall 2020 and spring 2021 experimental period, but conducted separately (1-3 and 4-6) as the spring and the fall sites were in different locations, and conducted at different seasons. Furthermore, different seasons theoretically attract different species of birds, there were more weather events in the spring than the fall, and images were counted days in the fall, whereas in the spring, were counted at very specified times. If combined, this could risk false effects as the fall might have more bird counts than the spring (See discussion).

The following ANOVA codes were written to understand the effect of explanatory variables (and species) on bird visitations, through an analysis of variance table, to investigate if bird visits to treatments may or may not have depended on such variables in this experiment: 1. An interaction with species and site, position and site, and site and treatment on bird visits; 2. An interaction between position, site and treatment on bird visits; 3. An interaction between species, site and treatment on bird visits and; 4. An interaction between site and treatment, and an interaction between position and treatment on bird visits. This order of analyses were narrowed from a larger code to a smaller code to understand how explanatory variables impact the number of visits to treatment and/or suet dough over time. If an explanatory variable did not seem to have an effect on the data (i.e., not significant across multiple codes), it was taken out to continue narrowing. These analyses were computed separately for the fall and for the spring. These ANOVA analyses were particularly important to understand the effect of bird visits when treatments were added to the system after the baseline, but did not compare treatments against each other (matte to shiny).

As the ANOVAs take into account the baseline data, a dplyr filter in R was used to omit this trial so that a more appropriate analyses of the types of treatments (matte and shiny interaction) could be analyzed. This was conducted because I wanted to understand bird attractiveness to vertically polarized light when given two choices. The ANOVA interaction codes from the previous analysis were used to find the significant interactions and analyze these further. A Mixed Model with species as a random effect, and site and/or position and treatment as fixed effects was run. This accounts for the variation introduced by different species' foraging behavior at different sites (forest, near wetland and forest edge). This was not a variable I could manipulate in my experiment. I ran a Mixed Model for both the fall and experimental periods.

I used the same baseline filter to analyze the six most abundant species, essentially creating another filter to analyze the effect of site and treatment and position and treatment on these specified bird visitations through an ANOVA. This was done as I wanted to see how certain species dictated overall bird visitation results. The following species were analyzed in the fall: Tufted titmouse, Black-capped chickadee, Blue jay, Red-bellied woodpecker, Downy woodpecker, and White-breasted nuthatch. The following species were analyzed in the spring: Black-capped chickadee, Dark-eyed junco, Red-bellied woodpecker, Downy woodpecker, and White-breasted nuthatch.

A Generalized Linear Mixed Model was used to further analyze the effect of the interaction between treatment and site on bird visits. This was done as a simple ANOVA is not the most appropriate analysis to be conducted on bird 'count' data as a response variable. This can invalidate results giving a false significance on a dataset that isn't properly analyzed. A GLMM on the other hand, can account for unbalanced data (i.e., more visits of one species at site one, less visits of the same species at site two), and gives more concrete conclusions about the effects variables pose on bird visit results and conclusions, while considering random effects used in a simple ANOVA. A GLMM was conducted for both experimental trials with the baseline filter.

Data visualizations were conducted in R using ggplot that takes into account positionality of the treatments, and species of birds. Scatterplots with average visits to treatments, and specified bird species, and boxplots were created to visualize data. Tables were created in Microsoft Excel.

3.6 *Sap Experiment*

Furthering the work by Horváth et al. (2019), I obtained natural Maple sap from a faculty member's maple tree to image its polarization properties. I also obtained natural Maple syrup for a comparison against sap.

I used bark from a Black birch, a log from a large branch of an unknown conifer (using the side bark of the log and the cross-section), a wooden block from an unknown tree and an unknown species of shrub that exhibited sapsucker holes. On the Black birch and the wooden block, a brush was used to paint one half of the bark and block with natural sap, and the other half with syrup. The side of the log was painted similarly: one half with natural sap, the other with syrup on the flattest part of the log. After imaging, the exposed, cross-sectional area of the log was painted with one half natural sap, and the other half with syrup. On a branch of the bush, natural Maple sap was painted generously to the holes and surrounding areas.

Similar to what was done with my treatments, I imaged the sap on each piece of wood through the Canon DSLR for the visible range, and the Nikon DSLR for the UV, which both had specified modifications that allowed them to image polarization properties (see section 3.2). Images were then imported into the AlgoNet® software and, similar to the process of imaging my treatments, I was able to see natural sap and Maple syrup's polarization abilities visually and statistically, as a percentage/degree. This was done creating a filter on a section of the object that would measure the polarization of that section. Tables were created in Microsoft Excel.

4 Results

My choice-field study was devised to experimentally test if birds can see or are attracted to vertically polarized light when given two options of food cues associated to two different trees with different treatments, polarized and nonpolarized (*Figure S1*). Sap and syrup painted on various bark and wood was imaged to answer the question if natural Maple sap polarizes light.

4.1 *Imaging*

Through imaging treatments, I had found that the shiny, black vinyl was a strong polarizer in the visible and ultraviolet range, and the matte, black vinyl was a strong depolarizer in the visible and ultraviolet range. This is based on the statistical results found through AlgoNet® (Reported is in the red color spectrum for visible: Shiny black vinyl Away from Sun= 90.7 degrees; Matte black vinyl Away from Sun = 16.06 degrees, Table 1a for positions and

UV). The visual properties also show its polarization: the shiny black surface is distinguished from its background, whereas the matte black surface blends in with its background (Table 1a, Figure 1a-b, Figure S2). From imaging maple sap on different shades of bark and wood (Figure 2) I found that when natural sap was painted on Black birch bark, polarization is higher in both the visible and ultraviolet range, but much more of a signal in the ultraviolet range than the visible range (Reported is red color spectrum for UV: Sap= 92 degrees; Syrup=77.2, Table 1b, Figure 2a). On all other objects, syrup was a better polarizer than natural sap, with the ultraviolet range's percent polarization higher than the visible range in all objects (Table 1b, Figure 2b-d). Sapsucker holes did not polarize much in the visible or ultraviolet range (Table 1b, Figure e-f). Polarization on each object is seen visually by distinguishing the darkness of the surface to its surroundings. Comparing Black birch bark to my treatments polarization properties, my treatments were a good simulator of natural sap, and a strong polarization signal in my experiment.

4.2 *Bird Visitation Analyses*

In order to make a conclusion about avian vertical polarization attractiveness based upon my data, a multitude of analyses were run to understand the role explanatory variables play in shaping bird visitations and species occurrence. For the fall experimental period, the final results from my GLMM analyses revealed that bird visits were site-dependent, but treatment alone was not a strong signal. However, the polarized, shiny treatment was a stronger signal than the position the treatments were placed in. In the spring, bird visits to the shiny treatment were site-dependent, but treatment alone was not a strong signal. In addition, bird visits were dependent on the position of the treatments, but the polarized, shiny treatment's signal alone *does* have an effect on bird visitations. Baseline data reveals that birds had a beforehand preference to the one tree over the other before the treatments were added into the system (Figure 7a,b). However, when treatments were added, the polarized, shiny treatment had more of a signal than the matte, depolarized treatment when each treatment were separately compared to the baseline data. These results show that birds may be able to detect vertically polarized light but only at certain sites and when the shiny treatment was in a certain position. In addition, out of the most abundant bird species that were analyzed, some species may have played a role in the site-dependent and position-dependent results, but they did not overwhelm or bias the data.

In R, several codes of interaction ANOVAs were run to understand the effects of explanatory variables and species, which could not be manipulated, on bird visitation. For these analyses, R takes into account the baseline data when computing the effects of treatments on bird visitations. Thus, the matte and shiny treatments were not analyzed against each other but to the baseline so that the effect is testing attraction when the treatments are added to the system. This was done to understand which treatment had a stronger signal to wild birds, and if this effect is site or position dependent.

For the fall experimental trial, in the analysis of the interactions of species and site, position and site, and treatment and site, treatment (F= 28.4, p=<0.01), species (F=20.7, p=<0.01), and site (F=43.6, p=<0.01) had an effect on bird visitations. Bird visitations to treatments was site-dependent (F=9.9. p=<0.01), and species presence was dependent on site (F= 8.4, p= <0.01). Position of treatments (A and B) was not significant (F=0.0062, p=0.94), and no following interactions with position were computed. Narrowing the analysis, site (F= 17.9 p=<0.01) and treatment (F= 11.7, p= <0.01) had an effect on bird visitations, and bird visitation to treatments were dependent on site location (F=4.09, p=0.018). Furthermore, bird visits to the matte treatment were site-dependent (t=2.03 , p=0.043), and bird visits to the shiny treatment were also site-dependent (t=2.76, p=0.006). Though installation of both treatments are conspicuous to birds after the baseline, the polarized, shiny treatment had more of a signal than the matte, depolarized treatment when comparing to the baseline data (Figure 3a, Figure 8a). Baseline data reveals that birds exhibited visitation preferences to one tree position over the other in all sites except for site 4 where there was no bias (Figure 7a,b). This was considered when treatments were installed into the system based on previous ANOVAs that compared baseline to treatment shiny and matte separately.

For the spring experimental trial, in the ANOVA analysis of the interactions of species and site, position and site, and treatment and site, species (F= 18.8, p=< 0.01) had an effect on bird visitations, and species was site-dependent (F=7.06, p=<0.01). In the analysis between position, site and treatment, bird visitation was dependent upon the position of the treatments (A and B) (F= 6.7, p=0.001), while site did not have an effect on bird visitations (F=1.68, p=0.2) and neither did specific treatments. In the final analysis between the interaction of position and treatment, position still dictated bird visits to the treatments (F=6.8, p=0.0014). In addition, bird visits to the shiny treatment was dependent upon position of the treatments (t= 2.4, p=0.017), while matte is not dependent on position (t=-1.2 , p=0.22) (Figure 3b, Figure 8b).

A Mixed Model with an interaction between site and treatment as fixed effects, with species as a random effect, furthered the finding from the ANOVAs that site had an effect on bird visitations for the fall experimental period (F=42.4, p=<0.01), but bird visits to the treatments did not depend on site (F=0.87, p=0.35). A Mixed Model with an interaction between position (A and B) and treatment as fixed effects, with species as a random effect, also furthered the finding from the ANOVAs that position of the treatments had an effect on bird visitations

(*F*=18.4, *p*=<0.01), with more birds visiting the shiny treatment than the matte (*t*=4.3, *p*=<0.01) for the spring experimental period. Baseline data was not incorporated in the Mixed Model as it was incorporated into the above ANOVA interactions, but similar results were uncovered.

To further the analysis, the results of the Generalized Linear Mixed Model with the interaction of site and treatment on bird visitations, excluding baseline data, revealed that, for the fall experimental period, bird visits are site-dependent (*z*=18.4, *p*=<0.01), but treatment is not a strong signal, though it suggests something could be occurring (*z*=1.8, *p*=0.07) (Figure 3a). In contrast, GLMM suggests that position does not have an effect on bird visitations to the treatments (*z*=1.006, *p*=0.3), but shiny treatment alone does have an effect on bird visitations (*z*=2.8, *p*=0.005) (Figure 3a, Figure 8a). GLMM results for the spring experimental period revealed that bird visits to the shiny treatment was dependent upon the location of the site (*z*=2.17, *p*=0.03), but treatment alone was not a strong enough signal, though it suggests that something could be occurring (*z*=-1.7, *p*=0.09). In addition, GLMM results for the interaction between position and treatment suggest that bird visitations to the shiny treatment were dependent upon the position the treatments were placed in (*z*=9.5, *p*=<0.01), and shiny treatment alone does have an effect on bird visitations to the treatments (*z*=-5.2, *p*=<0.01), but positionality interaction with the shiny treatment was a stronger effect than shiny treatment alone (Figure 3b, Figure 8b).

A dplyr filter for non-baseline data was applied for each abundant species in the data, and ANOVAs were run on this filter. This was to understand if certain species are driving the results of the experiment. Abundant species statistical results are only provided to understand how certain species drive visitation effects (Table 2). Baseline is included in the visualizations for comparison across species (Figure 4, 5), and baseline is excluded in the visualization among certain bird species who had an effect on site and position (Figure 6). For the fall, only site was significant, and ANOVAs between the interaction of site and treatment were used. For the spring, both site and position were significant, and ANOVAs between the interaction of site and treatment, and ANOVAs between the interaction of position and treatment were used. A variety of birds were attracted to my experiment which included ten species of songbirds (*Passeriformes*), and six species of woodpeckers (*Piciformes*), but the ones most abundant were found by summing the overall bird visits per species (Table S1). In the fall experimental period, the species of Blue jay, Downy woodpecker, White-breasted nuthatch and Tufted titmouse had an effect on bird visits to sites (Table 2a, Fig 4). In the spring experimental period, the species of Black-capped chickadee, Dark-eyed junco, and Downy woodpecker had an effect on bird visits to sites (Table 2b, Fig 5). Only Tufted titmouse had an effect on bird visits to treatments, and treatments did depend on the position they were put in for Tufted titmouse numbers (Table 2c, Figure 6f). These results explain that certain bird species are more abundant than others at certain sites and could affect the site-dependent results for the fall and spring, with only Tufted titmice playing a part in the results in the spring for position-dependent results for treatments (Figure 6f). Although certain species abundances may have an impact on visitations to site and treatments (Tufted titmouse position), it is clear based on the similar results of the ANOVA, Mixed Model and GLMM, that certain species abundances do not have an *overwhelming* effect on or bias the conclusions of the data, but they do display different effects and preferences particularly to sites, which is shown in *Figure 6*. This has nothing to do with treatment conclusions.

It should be stated that GLMM analyses do not match accordingly to *Figure 3a* and *b*, most likely due to the means (black square in graph) representative of the estimated marginal means. Essentially these figures take into account all the explanatory variables (position, type of treatment, site location) and species when computing the analysis. Thus, the statistical analysis should be interpreted on its own, whereas the figure is representative of the multifaceted interconnections of bird visits and variables dictated in this experiment and may not depict the best visualization though incorporating all variables. Further visualizations were created ignoring site-dependencies, as position seemed to have a stronger effect on bird visits than site dependencies, according to the GLMM analyses (Figure 8a,b). Bird visits were dependent on site, but bird visits to the shiny treatment alone was not a strong signal in either experimental period. When excluding site locations, and combining positionality, in both the spring and the fall, one can see visually the effects of the GLMM analysis that more birds visit the polarized treatment than the non-polarized treatment (Figure 8a,b), but it does not view as a strong effect as dictated in the statistics. For more of a detailed look at raw data: *Text S1*, *Figure S4* and *S5* depict raw visitation data with visualizations made in Microsoft Excel.

a Visible Shiny Towards Sun **b** Visible Matte Towards Sun

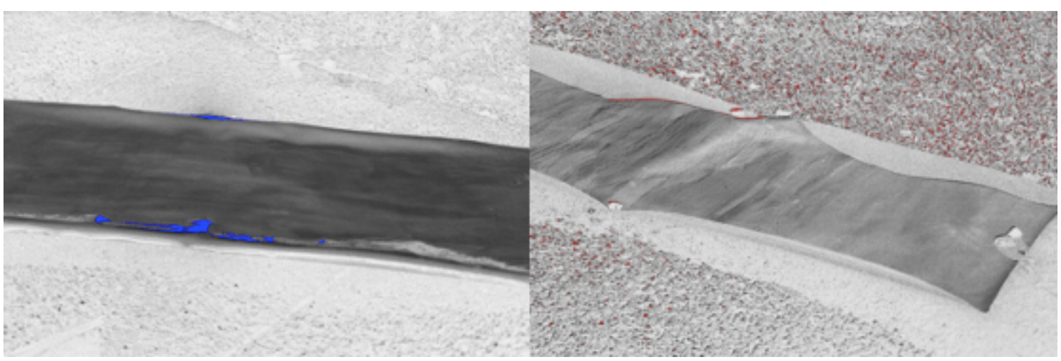


FIGURE 1 Visual comparison of shiny, polarized treatment (*a*), against matte, depolarized treatment (*b*) placed on black pavement to see distinguishing features. These the shiny treatment was used as a simulator of sap and the matte as a depolarizer to allow wild birds to make a choice between going to a feeder with a polarized treatment versus an unpolarized treatment. A Canon DSLR camera with a polarization filter was used to take pictures in the visible range, and AlgoNet® was used to analyze polarization properties of treatments from the pictures taken. Any red or blue portions are areas of overexposure and should be disregarded. Visible range is shown. See *Figure S2* and *Table 1a* for more visual comparisons, and ultraviolet comparisons.

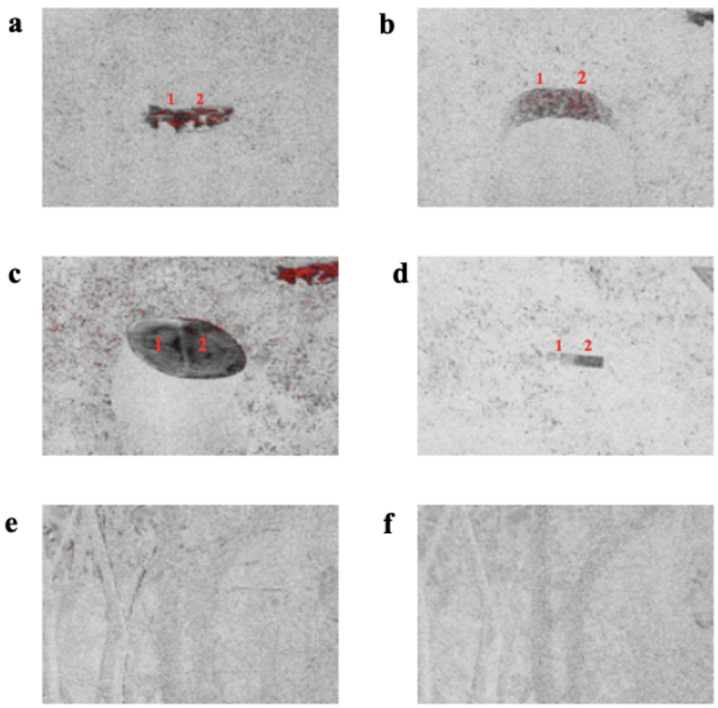
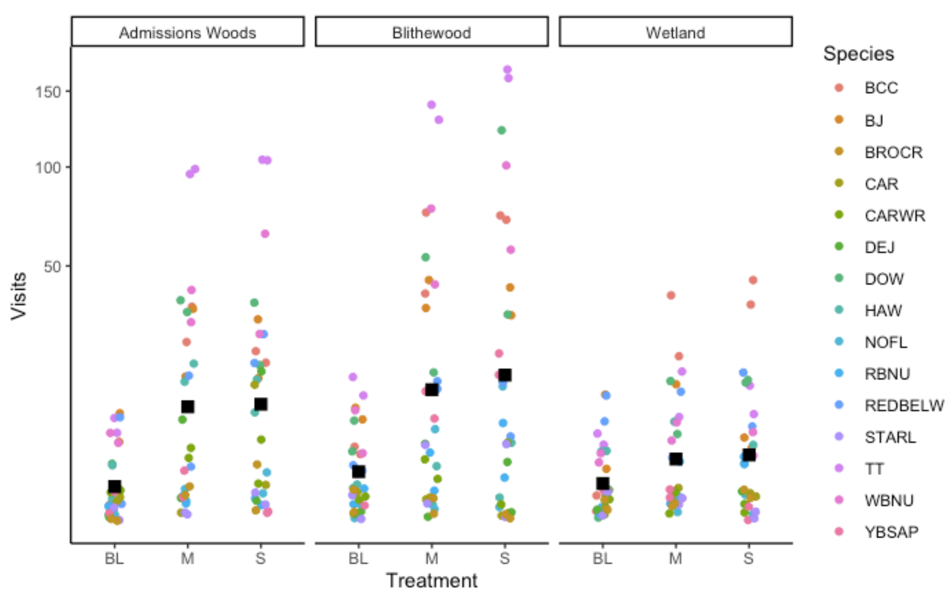


FIGURE 2 Visual comparison of birch bark (*a*), side of a log (*b*) and the cross-section of the log (*c*), and wooden block (*d*), when sap is painted on half of the object, and syrup is painted on the other half. The left side (1) was painted with sap and the right side (2) of each object was painted with syrup. Sapsucker holes (*e*) is without sap and sapsucker holes (*f*) is painted with sap painted along the holes. A Nikon DSLR camera with modifications was used to take pictures in the UV range, and AlgoNet® was used to analyze polarization properties of treatments from the pictures taken. UV range is shown. See *Table 1* and *Figure S3* for more visual comparisons, and visible comparisons.

a Fall Experimental Period



b Spring Experimental Period

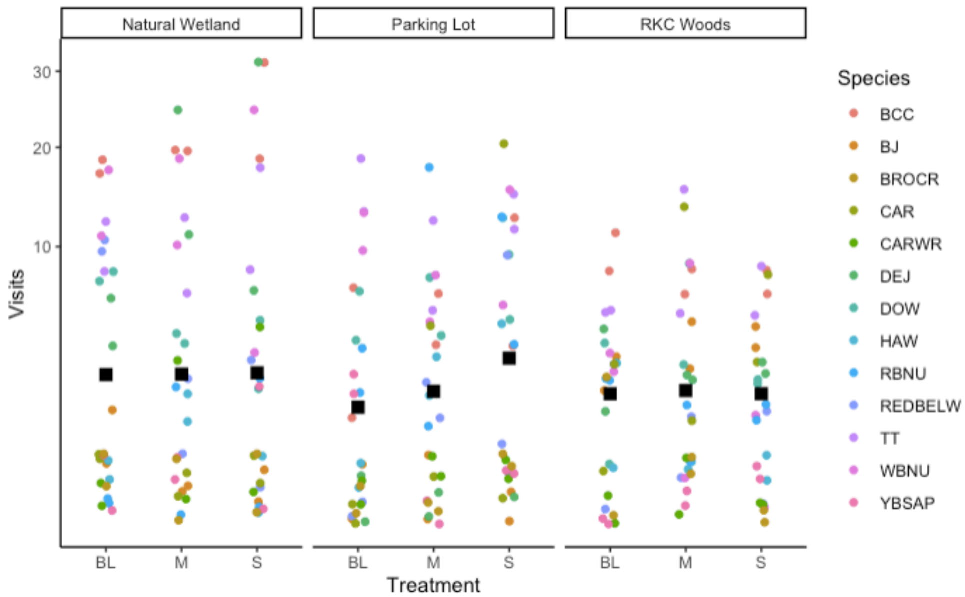


FIGURE 3 Bird visitation visualization for treatments (BL-baseline, M-matte, S-shiny) at each site for the fall 2020 (*a*), and the spring 2021 (*b*) experimental periods. Values on the y-axis represent bird visitation counts similar to a log-scale, and black squares are overall averages. A square root transformation was used to adequately display count data that varied over a wide range and not evenly distributed, and visualizations only display fixed effects. *Visits are measured in bird counts over time.* Position was taken into account in the visualization, and species are colorized on the right. R was utilized to make visualizations with ggplot. Bird codes: BCC=Black-capped chickadee; BJ=Blue jay; BROCR=Brown creeper; CAR=Cardinal; CARWR=Carolina wren; DEJ=Dark-eyed junco; DOW=Downy woodpecker; HAW=Hairy woodpecker; NOFL=Northern flicker; RBNU=Red-breasted nuthatch; REDBELW=Red-bellied woodpecker; STARL=European Starling; TT=Tufted titmouse; WBNU=White-breasted nuthatch; YBSAP=Yellow-bellied sapsucker.

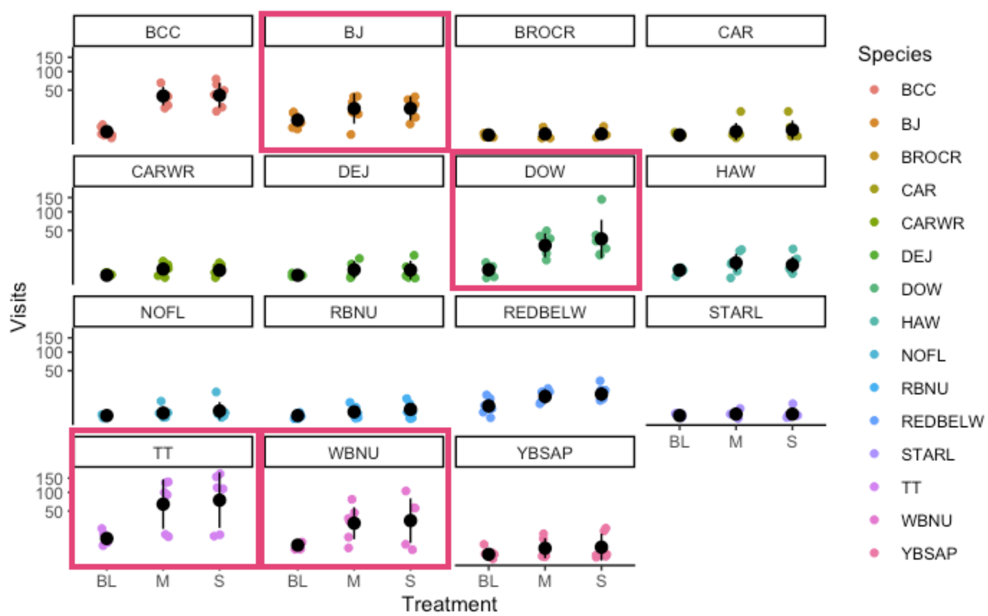


FIGURE 4 Bird visitation visualizations for bird species in the fall 2020 experimental trial for baseline (BL) matte (M) and shiny (S) treatments. Site and position were not taken into account when creating this graph. Most abundant birds that were analyzed and found to have an effect on bird visitations at different sites are outlined in pink. A square root transformation was used to adequately display count data that varied over a wide range and not evenly distributed, and visualizations only display fixed effects. *Visits are measured in bird counts over time.* R was utilized to make visualizations with ggplot. Bird codes: BCC=Black-capped chickadee; BJ=Blue jay; BROCR=Brown creeper; CAR=Cardinal; CARWR=Carolina wren; DEJ=Dark-eyed junco; DOW=Downy woodpecker; HAW=Hairy woodpecker; NOFL=Northern flicker; RBNU=Red-breasted nuthatch; REDBELW=Red-bellied woodpecker; STARL=European Starling; TT=Tufted titmouse; WBNU=White-breasted nuthatch; YBSAP=Yellow-bellied sapsucker.

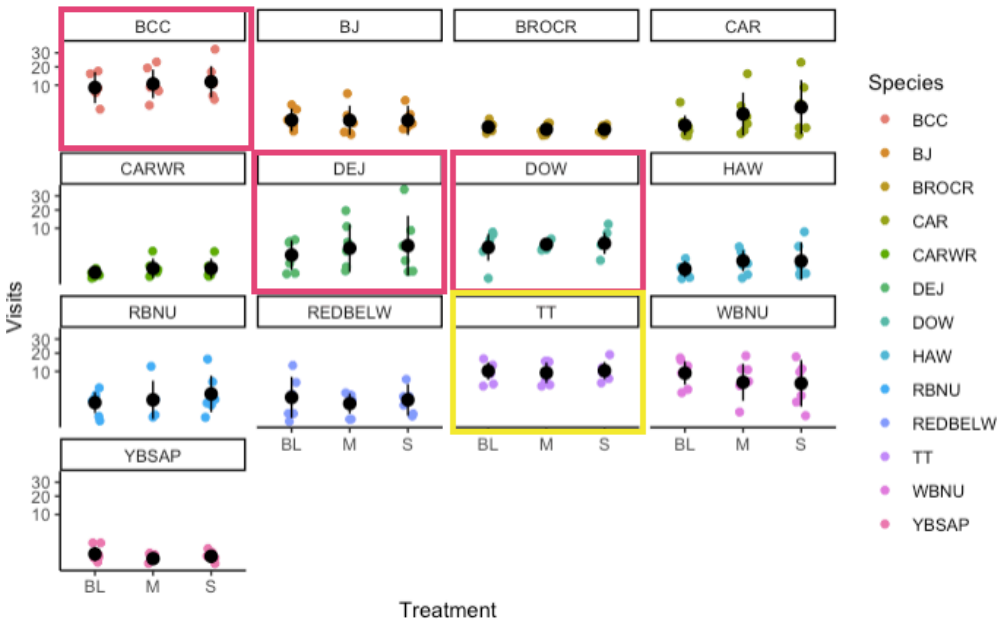
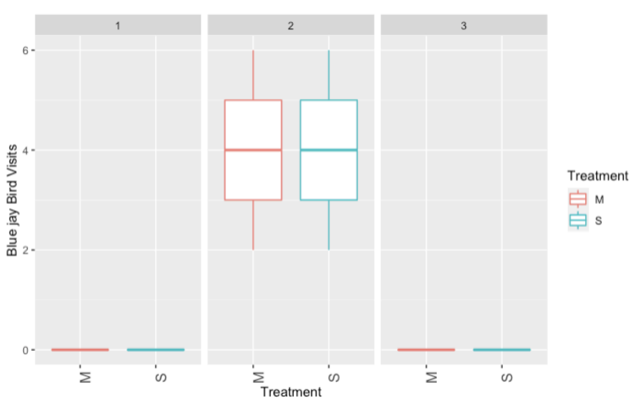


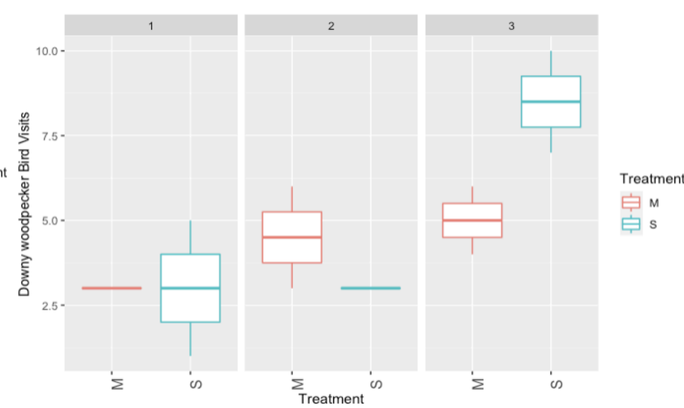
FIGURE 5 Bird visitation visualizations for bird species in the spring 2021 experimental trial for baseline (BL), matte (M) and shiny (S) treatments. Site and position were not taken into account when creating this graph. Most abundant birds that were analyzed and found to have an effect on bird visitations at different sites are outlined in pink, and at different positions outlined in yellow. A square root transformation was used to adequately display count data that varied over a wide range and not evenly distributed, and visualizations only display fixed effects. *Visits are measured in bird counts over time.* R was utilized to make visualizations with ggplot. Bird codes: BCC=Black-capped chickadee; BJ=Blue jay; BROCR=Brown creeper; CAR=Cardinal; CARWR=Carolina wren; DEJ=Dark-eyed junco; DOW=Downy woodpecker; HAW=Hairy woodpecker; RBNU=Red-breasted nuthatch; REDBELW=Red-bellied woodpecker; TT=Tufted titmouse; WBNU=White-breasted nuthatch; YBSAP=Yellow-bellied sapsucker.

a Fall 2020 Experimental Period

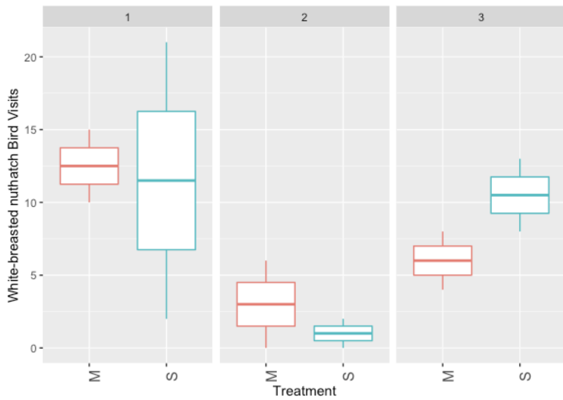
Blue jay



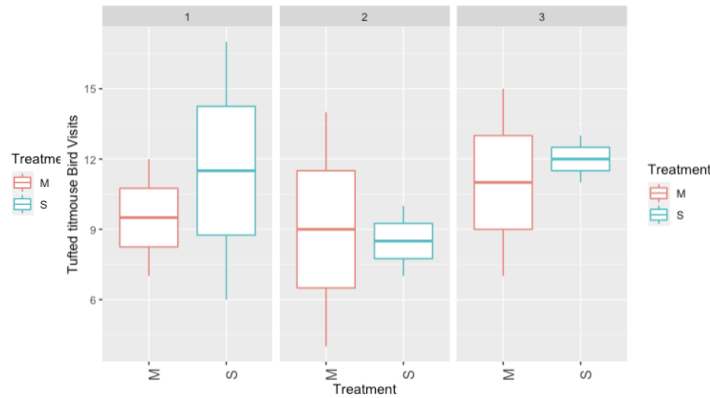
Downy woodpecker



White-breasted nuthatch

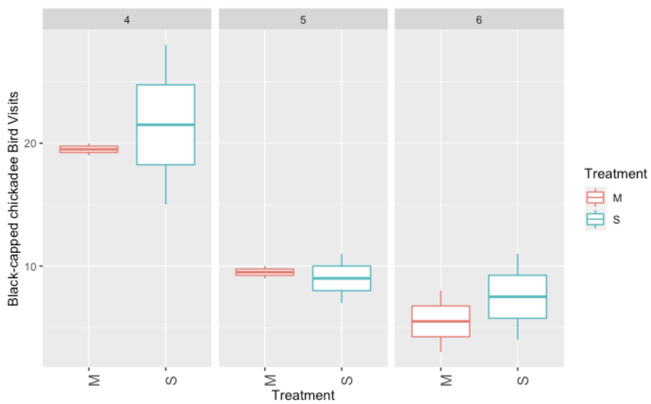


Tufted titmouse

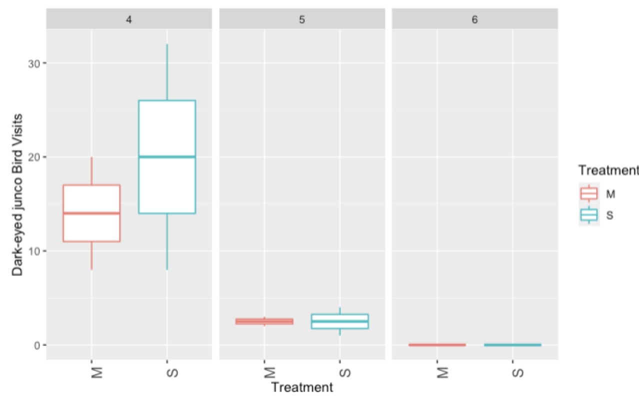


b Spring 2021 Experimental Period

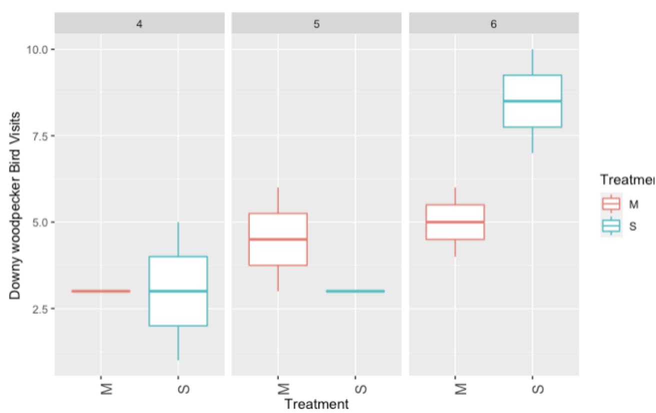
Black-capped chickadee



Dark-eyed junco



Downy woodpecker



Tufted titmouse (*Position*)

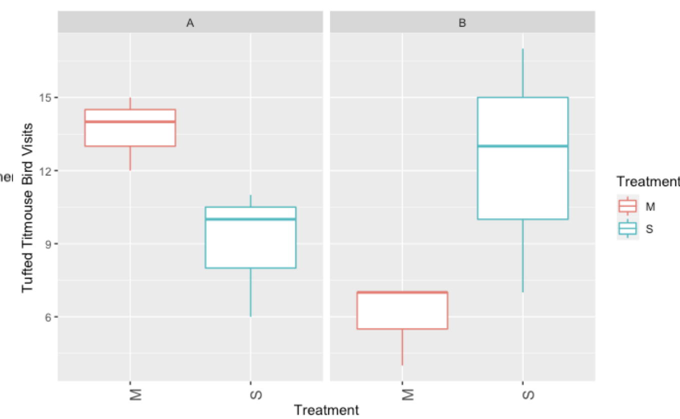
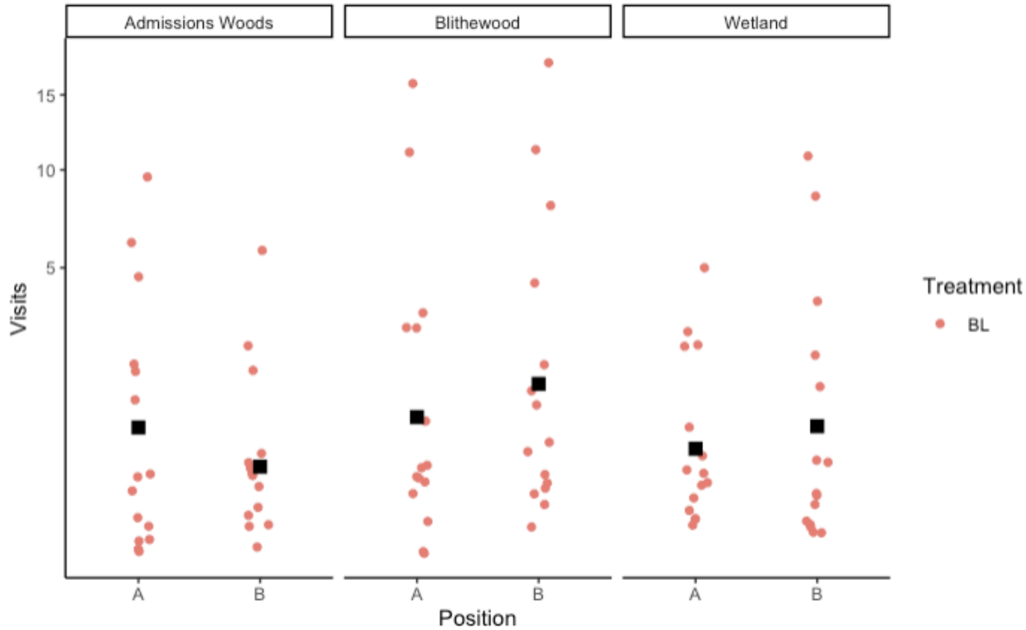


FIGURE 6 Bird visitation visualizations for species who dictated bird visitations to treatments for the fall 2020 (*a*) and the spring 2021 (*b*). Interaction between site and treatment is shown in all species except for Tufted titmouse in (*b*) where positionality effected species visitations. Only matte (M) and shiny (S) are shown. *Visits are measured in bird counts over time.* A dplyr filter was used to excuse the baseline data to make a clearer relationship. R was utilized to make visualizations with ggplot.

a Fall Baseline



b Spring Baseline

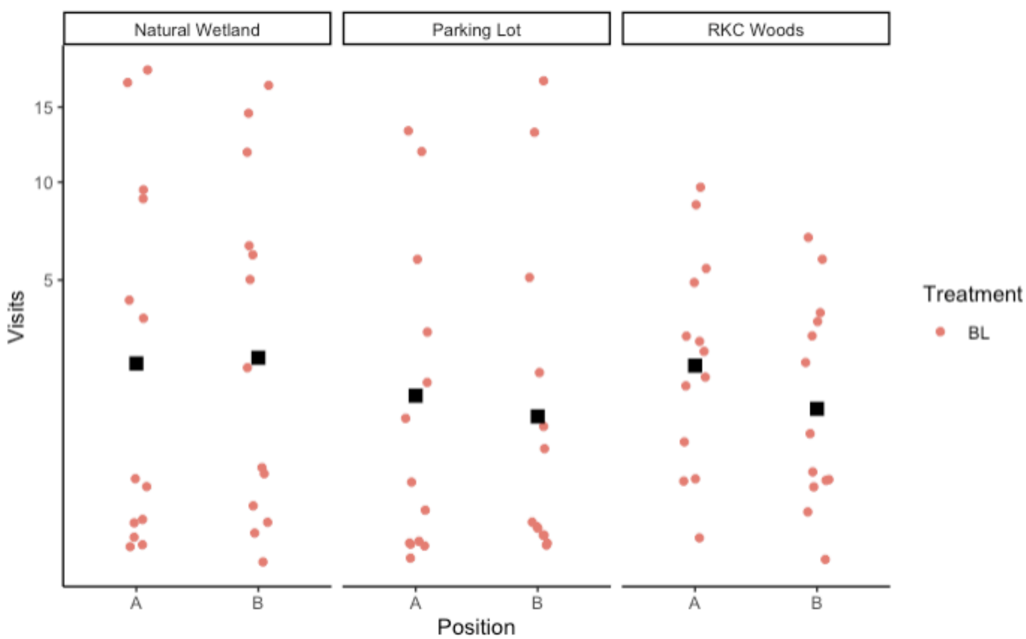
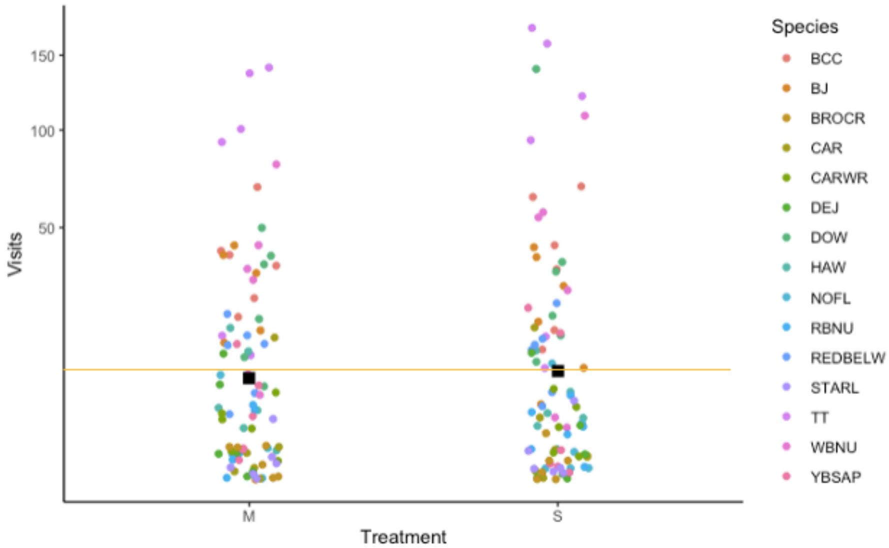


FIGURE 7 Bird visitation visualizations across species for only the baseline data to interpret bird preferences before the experimental trials for the fall (*a*) and the spring (*b*). A and B represent left and right tree positions respectively. Sites are noted. A dplyr filter was used to matte and shiny treatments. Values on the y-axis represent bird visitation counts similar to a log-scale, and black squares are overall averages. A square root transformation was used to adequately display count data that varied over a wide range and not evenly distributed, and visualizations only display fixed effects. *Visits are measured in bird counts over time*. R was utilized to make visualizations with ggplot.

a Fall Experimental Period



b Spring Experimental Period

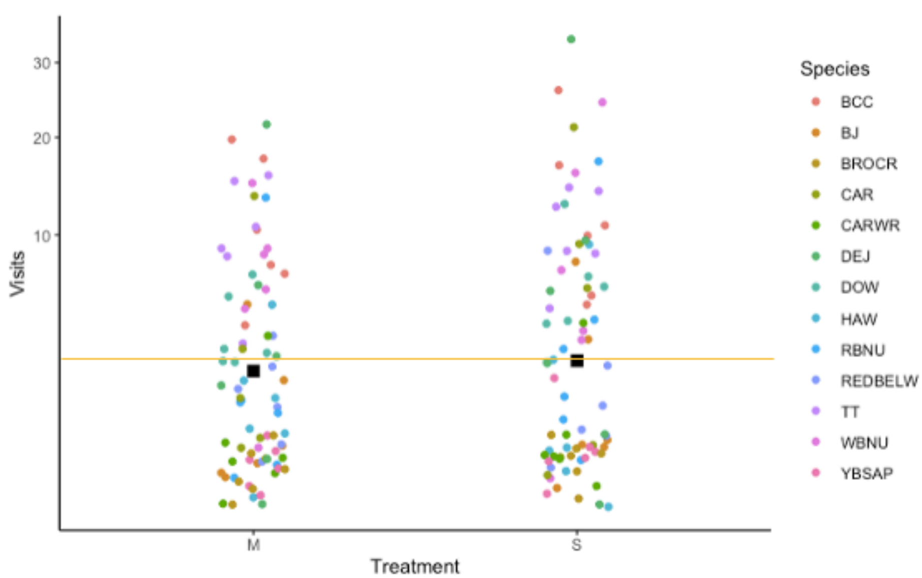


FIGURE 8 Bird visitation visualization across species and excluding site locations from visualizations to depict the effect treatment matte (M) and shiny (S) have on overall avian attraction. Values on the y-axis represent bird visitation counts similar to a log-scale, and black squares are overall averages. A square root transformation was used to adequately display count data that varied over a wide range and not evenly distributed, and visualizations only display fixed effects. Position was taken into account in the visualization, and species are colorized on the right. A yellow line is placed across the average points to display slightly more than average visits to the shiny treatment than the matte treatment, but this is not too evident in a square root transformation (See *Text S1, Fig. S4, S5*). *Visits are measured in bird counts over time*. R was utilized to make visualizations with ggplot. Bird codes: BCC=Black-capped chickadee; BJ=Blue jay; BROCR=Brown creeper; CAR=Cardinal; CARWR=Carolina wren; DEJ=Dark-eyed junco; DOW=Downy woodpecker; HAW=Hairy woodpecker; NOFL=Northern flicker; RBNU=Red-breasted nuthatch; REDBELW=Red-bellied woodpecker; STARL=European Starling; TT=Tufted titmouse; WBNU=White-breasted nuthatch; YBSAP=Yellow-bellied sapsucker.

a Treatments

VISIBLE	Color Spectrum		
Treatment and Position	Red	Green	Blue
Shiny Towards Sun	60.5	65	67
Shiny Away from Sun	90.7	87.7	83
Matte Towrds Sun	42.2	45.2	42
Matte Away from Sun	16.06	14.3	11.3

UV	Color Spectrum		
Treatment and Position	Red	Green	Blue
Shiny Towards Sun	84.3	76.7	80.7
Skylight Polarization	70.2	69.3	69.1
Matte Towards Sun	33.7	23	26.6
Matte Away from Sun	12.7	8.8	10.9

b Sap and Syrup

VISIBLE	SAP			SYRUP		
Object	Red	Green	Blue	Red	Green	Blue
Birch Bark	42	50	51	33	40.5	44
Log Side	37	41	44	43	47	49
Log Cross-Section	2.08	4.5	6	6	11.5	18
Wooden Block	5.2	10.5	17.8	3.4	8.5	14.2
	NO SAP			SAP		
Object	Red	Green	Blue	Red	Green	Blue
Sapsucker Holes	9	10.2	12.3	12	15	19

UV	SAP			SYRUP		
Object	Red	Green	Blue	Red	Green	Blue
Birch Bark	92	86	90.1	77.2	76.4	77.1
Log Side	66.6	51.8	60	66.7	66.4	67.5
Log Cross-Section	66.6	44.8	56	70.4	51.2	62.4
Wooden Block	33.5	22.3	26.6	72.9	54.6	63.8
	NO SAP			SAP		
Object	Red	Green	Blue	Red	Green	Blue
Sapsucker Holes	17	9.8	12.3	20.2	10.8	13.5

TABLE 1 Percentage/degree of polarized and nonpolarized treatments (*a*), when placed in different positions on the ground, and percentage/degree of sap and syrup (*b*), when painted on various pieces of bark and wood, at which the beforementioned objects polarize light in the visible (yellow) and ultraviolet (pink) ranges. Red, blue and green represent color spectrum. Statistical measures were computed through AlgoNet®, through importing images from the Canon and Nikon DSLR cameras with modifications. The higher the number of the degree or percentage, the greater the treatment or object polarizes.

a Fall (Site and Treatment)

Species Common Name	*F*-value	*p*-value
Black-capped chickadee	0.003	0.96
Blue jay*	47.7	<0.01
Downy woodpecker*	6.1	0.04
Red-bellied woodpecker	0.82	0.4
White-breasted nuthatch*	24	<0.01
Tufted titmouse*	195.17	<0.01

b Spring (Site and Treatment)

Species Common Name	*F*-value	*p*-value
Black-capped chickadee*	17.15	0.003
Dark-eyed junco*	9.9	0.014
Downy woodpecker*	7.6	0.02
Red-bellied woodpecker	0.3	0.59
White-breasted nuthatch	0.29	0.61
Tufted titmouse	0.02	0.88

c Spring (Position and Treatment)

Species Common Name	*F*-value	*p*-value
Black-capped chickadee	0.1	0.76
Dark-eyed junco	0.8	0.4
Downy woodpecker	1.88	0.21
Red-bellied woodpecker	2.34	0.16
White-breasted nuthatch	3.6	0.09
Tufted titmouse^``	9.6	0.01

Significance Codes

*Significance of Site
^Significance of treatment
`` Significance of interaction Position
No significance: interaction reported

TABLE 2 Reported significance values of the most abundant species when in interactions between site and treatment (*a*, *b*), and position and treatment (*c*) for the fall 2020 (*a*, *b*) and the spring 2021 (*c*) experimental trials. Computed to understand the effect and influence that certain species had on bird visitations to treatments when coupled with previously determined significant explanatory variables (position and site). R was utilized to make several ANOVAs, a Mixed Model and GLMM to determine variables that had an effect on bird overall visitations when species was and was not incorporated into the analyses, and then a filter was applied to excluded baseline data, and select abundant species for a following ANOVA to receive values in this table.

5 Discussion

Birds use a variety of mechanisms and cues from their environment to find food, which guide their foraging behavior (Sustaita et al., 2018). This study was designed to deduct conclusions about bird foraging behavior when birds are presented with two choices, and have to make decisions in how best to nourish themselves when faced with two choices (Rojas-Ferrer & Morand-Ferron 2020). More bird visits to the shiny, polarized, treatment than the depolarized, matte, treatment over time, signaled bird attraction to polarized light. I conducted a choice-field experiment to answer two questions: (1) Can birds see vertically polarized light when given a food-associated cue, and a choice between two treatments, one that polarizes light and one that is non-polarized?; and (2) Is natural Maple tree sap polarized? My study provides experimental evidence that wild birds are attracted to and can detect vertically polarized light, and use this to find food. These results are site-dependent and dependent upon the position of the treatment, with some bird species having a role in mediating bird count abundances, but this is not overwhelming or biasing my conclusions. Imagery results of natural Maple sap and Maple syrup indicate that natural Maple sap polarizes light the most when placed on Black birch, but in all other wood objects, syrup is a stronger polarizer. In both sap and syrup, the ultraviolet range polarizes more light than the visible range. My imagery shows that my treatments were strong polarizers and depolarizers respectively in both the visible and ultraviolet range. This suggests that my polarized vinyl treatments were a sufficient proxy for natural Maple sap, and even syrup. Furthermore, based on my findings of sap polarization, birds may use natural sap's polarization properties on bark similar to Black birch to locate food, suggesting a potential reason why birds may be able to detect vertically polarized light.

5.1 *Bird Attractiveness to Polarized Light and Variable Dependencies*

5.1.1 Site-dependencies

Wild birds are attracted to vertically polarized light when given a food-associated cue. My Generalized Linear Mixed Model results reveal that avian attraction to polarized light is site-dependent and position-dependent, but this entails *different interpretations* for the fall and the spring. In the fall, bird visits were site-dependent, regardless of treatments presence. This means that birds did not seem to be attracted to the signal of polarized light comparatively across sites in the fall. Rather, different site locations attracted different species of birds, unrelated to treatment. In the spring, bird visits were also site-dependent, but birds *were* attracted to the signal of the polarized, shiny treatment over the depolarized, matte treatment. This suggests that site location had an impact on bird visits to the polarized, shiny treatment. However, the shiny treatment alone *was not* a strong enough signal to the birds, suggesting that location of polarized light cues in a forest, wetland or a forest edge is crucial for bird attraction. Though the shiny treatment was dependent on site location, site location seemed to be a stronger attractor than the treatment itself, similar to the fall experimental trial.

This could be for several reasons. First, site locations were varied in the types of habitats: interior forests (Fall: Site 1-Wetland, Site 2-Admissions Cottage; Spring: Site 6-Parking lot), forest edges (Fall: Site 3-Blithewood; Spring: Site 5-RKC), and near to a natural wetland (Spring: Site 5-Natural Wetland). There may be a feature at one site than another site that attracts more birds on average to an experimental site, regardless of the treatments, comparatively to all other sites. For example, the wetland near to site 5 might be a site where many birds go to forage, and could be a distinguishing feature of this site. When the treatments are placed on the trees, birds may believe them to be conspicuous, regardless of polarization properties, such that the birds from the wetland visit the feeders. But in the spring, the shiny treatment did dictate signal, with some sites having more bird visits than other sites (i.e., higher overall bird visits to site 5, lower overall bird visits to site 6).

Second, there could be different resources available for birds that exist outside the experiment, and different needs for birds to visit a food source. Based on bird's thermal energetic demands in colder weather, birds need to eat more food to stay warm (Brittingham & Temple, 1992; Meehan et al., 2004). When there may not be as many available resources around due to the winter period or colder weather, birds may seek out alternative food sources, such as suet dough, to meet their thermal demands. One site may be colder than the other, such as site 3, as it is located near the Hudson River and experiences greater wind. This may dictate bird visits to feeders regardless of the treatments placed on the tree.

Third, different locations have different forest covers, and this could dictate why in the spring the shiny treatment was site-dependent. In the interior forests, there is more shade and not a lot of direct sunlight. In edge habitats, more sun is displayed on the treatments. Thus, if there is more canopy cover, it would make sense that the treatment signal across sites is not a strong enough signal as compared to site location. The spring sites were located in more “open” areas as compared to the fall sites, unintentionally. This could be why the shiny treatment was more of a signal than in the fall, but still was site dependent. Exposing treatments to birds in forest edges or grasslands may change the polarized signal across sites.

Finally, birds may chose sites based on other habitat selection mechanisms (Hildén 1965; Jones 2001). Birds make choices in how best to survive. Perhaps certain sites have predators, such as a large mammal or a raptorial species that may deter songbirds from visiting a particular site. This would cause lower bird visits to one site over the other outside the scope of vertically polarized attraction. In the spring, since more birds visited the shiny treatment and site did have an impact on bird visitations, it could be said that there were different habitat selection methods, or different foraging behaviors that could have been based on factors outside the experimental study, such as predator presence. It could also be said that certain sites may have birds that have preferences to polarize light, whereas in the fall, there was no preference such that polarize light did not dictate site-dependent results. This suggests a need to expand site-wise to understand how different sites may render different results on bird attractiveness to vertically polarized light.

5.1.2 Position-dependencies

In the fall, bird visits to the shiny treatment were greater on average than the matte treatment, no matter what position the shiny treatment was placed in: the polarized, shiny treatment *alone* was a strong enough signal to attract birds to the polarized treatment over the depolarized treatment. Similarly, in the spring, bird visits to the polarized, shiny treatment were greater on average than bird visits to the depolarized, matte treatment. However, the polarized treatment alone *was not* a strong enough signal to attract birds to the treatment, and position interaction with the treatment was stronger. This suggests that the position that the shiny treatments were placed on the trees (A and B) had an effect on overall bird visits, when in the fall, position mattered, but the shiny treatment alone was more powerful in of itself.

Positionality could matter for several reasons. First, similar to how canopy cover may dictate bird visits in site-dependencies, position results may also be dependent on light availability (Horváth & Hegedüs, 2014) compared to tree A to tree B. Tree position A at a particular site may have more shade than tree B due to a shrub or another tree hiding the polarized cues of the treatment. Though in the fall this may not have mattered, in the spring, the shiny treatments may have been dependent on the position that had more sun cover than the other position. In addition, treatments were oriented on the North side of the tree. Perhaps one tree had more sunlight at one time than at another time (sunrise and sunset) (Moore 1986; Muheim et al., 2011). This may have an effect on bird visitations according to the side of the tree the treatment and associated feeder were facing the camera.

Second, one position may have a feature that another tree position does not. Tree position B at a particular site may have a berry shrub next to it or a sapling where birds prefer to perch. This might attract more bird visits to position B than to position A. Although more bird visits to the shiny treatment were still observed at both positions, it is dependent on being situated in that position B where the signal of the treatment is higher than in position A. This more so has to do with bird preferences and habitat selection processes (Hildén 1965; Jones 2001) beyond the controls and confines of this experiment.

Third, different species of trees have different types of bark textures. One tree may exhibit bark that is smoother that treatments could easily be wrapped around, but another tree may exhibit bark that is rougher which makes treatment fastening difficult. Though this would not change bird attraction to polarized light, it may make cues at one tree position slightly stronger than the other. It could be argued that species of trees and texture could matter, but treatments were rotated, and in each rotation, the polarized, shiny treatment exhibited, on average, more bird visitations than the matte treatment. This makes more of a case for the fall experiment where the shiny treatment alone is a stronger signal than positionality. Effectively, features of the positions were ignored because the polarized, shiny treatment overpowered visitations. In the spring, despite rotations, positionality was coupled with bird visits to the polarized shiny treatment. Species here could have been considered, as well as the distance away from the two study trees. However, in each case, the polarized, shiny treatment still attracted on average more visitations the depolarized treatment, despite its coupling with position.

5.2 *Species-specific Preferences*

My ANOVA analyses for the fall experimental trial revealed that of the most abundant birds analyzed, the Blue jay, Downy woodpecker, White-breasted nuthatch and the Tufted titmouse played a role in the differences in bird visits to site locations. The Black-capped chickadee, Dark-eyed junco, and Downy woodpecker had a part in the differences of bird visits to sites in the spring experimental period. Only did the Tufted titmouse in the spring, when analyzed against position, had an effect on polarized treatments across sites. Similar to section 5.1.1 in site-dependencies, different species are more abundant at different sites, and could dictate the differences in bird visitations across sites. This could be as a Black-capped chickadee might prefer the features of a wetland site whereas a Downy woodpecker might prefer the features of a forest. Tufted titmice, who had an effect on treatment positionality, may have preferred one tree over the other due to features of that tree position like a shrub nearby. However, although these species are abundant and played a role in site-mediated visitations and in the case of the titmice, positionality-dependencies, data analyses revealed that these species did not seem to overwhelm the results of the experiment. This suggests that bird more birds on average visited the feeder with an associated polarized treatment over a feeder with an associated nonpolarized treatment.

Though abundant birds who played a role in site-mediated dependencies could have masked the effect on treatments, my results suggest that certain species abundances in themselves was not the cause, and rather, there were other factors outside the experiment that may have dictated differences in species' preferences. It could be argued that, for the spring experimental trial, Tufted titmouse may be the only specified bird species of whom dictates bird visitations to treatments as an effect of position. However, if this were the case, then adding other species, coupled with other variables, would have not suppressed this signal of the titmouse. Instead, the same results were shown, statistically and visually when including other variables. This also suggests that there were other factors outside the experiment that may have impacted species' preferences.

5.3 *Baseline Preferences and Conspicuousness*

The baseline data reveals that birds prefer to go to one tree position over the other, and this was observed across all sites, except for site 4 where there was no bias to one tree over the other. This furthers the above theories that bird preferences may be based on the facets of the environment that dictate preferences to positionality. Baseline data also reveals that no matter how close trees were in relation to each other, under 5 feet, birds still went to one position feeder over the other position feeder.

However, based on ANOVA comparisons with treatments, more birds on average visited both of the treatments than when there were no treatments in the system. This argues for overall conspicuousness amongst both treatments no matter its polarization. There was a drastic difference in the fall visitations than the spring visitations with treatments, perhaps due to overall image counting methodologies, whereas if methodologies were kept similar, there may have been similarities with the fall data. Similar to the GLMM models, the ANOVAs with multiple interactions suggested that, even though both treatments were conspicuous in a site location, the polarized, shiny treatment in both seasons was more conspicuous than the depolarized treatment. This means that any beforehand bias in the baseline period was eliminated when the treatments were put on the tree, with more bird visits going towards the shiny treatment than the matte treatment when they were compared to the baseline (See Supplementary Text). Though a similar conclusion to my GLMM analyses, this conclusion does not compare matte to shiny explicitly, but matte to baseline and shiny to baseline separately. This could suggest that such cues could overwhelm a habitat when they are first introduced, and implies that birds must use some element of polarization to navigate and to forage. A lower number bird visits in the baseline and a high number of bird visits in the experimental trials supports the theory that birds must be detecting vertical polarization cues either in the visible or the ultraviolet, and being strongly attracted to them in order to carry out foraging behavior (Pinzon-Rodriguez & Muheim 2017) My shiny treatment was a strong polarizer based off of statistical analyses, which suggests that birds must be using some elements, if not all elements of vertically polarized light to find the suet dough as a behavioral response to seeing light.

5.4 *Understanding Avian Attractiveness to Vertically Polarized Light*

My results expand on previous research that tested the orientation and foraging behaviors of migratory birds when placed in hexagonal, octagonal and circular cages in lab experiments in the horizontal plane (Able 1982; Helbig et al., 2010; Moore 1986; Moore & Phillips 1988; Muheim et al., 2016; Philips & Moore 1992; Wiltschko et al., 1972). My field-based study did not test for orientation, other than placing the experiment on the North-facing side of the tree, but similarly used cues to guide foraging behaviors of birds, but in a different plane of orientation. A diverse variety of birds were attracted to my experiment including ten species of songbirds (*Passeriformes*), and six species of woodpeckers (*Piciformes*). This expands and reinforces the list of bird species (warblers: Philips & Moore 1992; Able 1977; sparrows: Able 1982; Robertson et al., 2021 *in prep.;* chickadees: Duff et al., 1998; Robertson et al., 2021 *in prep*.; jays: Duff et al., 1998; Wiltschko et al., 1999; pigeons: Muheim 2011; woodpeckers: Robertson et al., 2021 *in prep.;* and other songbirds specifically in field-based studies: Robertson et al., 2021 *in prep.*) who may be able to detect polarized light in the visible and ultraviolet range.

Pinzon-Rodriguez & Muheim (2017) found that Zebra finches' magnetic compass only works when they are given polarized cues in a cage experimentation. This suggests that polarization cues could be coupled with factors outside the location of a site, or the position of treatments or signals such as in my experiment. Rather, it could be coupled with another *cue* that furthers the behavioral response in sensing food sources in a complex environment. A further study may investigate how wild birds' polarization ability is coupled with their magnetic compass in a field-based approach.

A previous field-choice experiment conducted by Robertson et al. (2021; *in prep*.) designed several experimental trials to investigate how birds respond to horizontally polarized light signals in the context of foraging behavior, using color-polarization bird feeders, simulating bodies of water through differentially polarized ground panels, and producing differently polarized and heated bird baths. Their results suggest that wild birds can locate sources of polarized light and use this to guide their decisions, and this finding is taxonomically widespread. Though abundant species in my dataset did not overwhelm the results of the experiment, their abundances were most likely mediated by factors outside the environment that played a role in explanatory variable dependencies such as site location. This suggests a need for future studies that test bird responses to polarization in the natural environment to be analyzed with controlled and uncontrolled factors such as site, position, and species in my experiment. This is to understand if birds are going to the polarized treatment because it is a strong signal in itself, or if they are visiting because of environmental facets outside of the experiment, while treatments just so happen to be present and conspicuous.

Artificial objects may be conspicuous to birds, but my study suggests that birds make a choice to go to the artificial object that vertically polarizes light over the one that does not polarize light in both experimental periods, similar to the findings of Robertson et al. (2021; *in prep.*) in multiple choice field experiments. My polarized vinyl treatments also mimicked similar properties of water, and even sap, suggesting that birds, when rotating their heads 90 degrees, could have used polarized cues similar to water to find food. It is suggested from this experimental data that birds use the sun to guide an aspect of foraging behavior, but how they can see polarized light, and how, evolutionarily, they have developed this skill is unknown.

Despite this, one major caveat that could have driven the results of my experiment is competition of resources. Although suet dough amount was controlled at both sites, such that each site had the same amount of food, at any given time, for unknown reasons, there could be more birds at one feeder than there are at another. If a Blue jay is at a feeder associated with a polarized treatment, an incoming Black-capped chickadee may go to the other feeder that is a strong depolarizer just because of the presence of a notoriously dominant bird at the polarized treatment. To control for this would be to count bird species when there is not another species of bird simultaneously at the other feeder, though this is quite difficult given the constraints of a camera operator. Predation also could have had an effect on bird choices in a complex environment. It could be said that birds may have had to make choices besides the choices of the experimental approach such as the tradeoff between starvation and predation (Bonter et al., 2013). This could be where birds choose to go or not to go to a feeder based on the presence of a predator in a habitat. Polarized cues could have guided them, but it is unclear in such a situation how birds would use such cues in moments of danger.

5.5 *Simulated Sap and Treatments*

My experiment also expands on Horváth et al. (2019)'s research of simulated sap, as images of natural Maple sap using a modified camera showed that Maple tree sap and Maple syrup polarizes light at a greater degree in the ultraviolet range than the visible range. This could mean that in the ultraviolet, or UV range, wood properties account for differences in different ranges. Tree sap was highly polarized when painted on the Black birch as compared to Maple syrup, whose polarization degree was higher when painted on other objects. This could mean that wet bark or sap bark on smooth surfaced bark could be the second source of UV polarized light, where the first is water. In addition, the exposed cross section of the log polarized a great amount of light in the UV, with a higher degree on the side of the log that was painted with syrup. Despite the rough profile of the cross-section, the log essentially soaked in the sap and the syrup, but instead of it disappearing completely within the fibers of the log, it was theorized the log kept the sap and syrup at the top of the cross section in small puddles or meniscuses. Eventually, this water would be soaked through the fibers or evaporated, but it could reveal insights into the polarization of bare trees in the forest when sap or rain encounters the hardwood. For example, excavated trees from insects or woodpeckers, a tree that lost bark, or a fallen tree may expose the hardwood to water or sap that could be polarized and detected by birds in the UV range. This is a novel finding. In a greater context, these results suggest that, in Nature, songbirds and woodpeckers use polarization of water and sap to find food in a complex environment.

Horváth et al. (2019) conducted a study based off a theory that tree sap or amber polarizes light. Using three different amber simulated experiments, they measured the attractiveness of insects to their treatments. Overall they found that when the simulated amber was placed horizontally, insects were attracted to it. However, when the simulated amber was placed on the tree in a vertical position, Horváth et al. (2019) found that insects were not attracted to the polarized treatment. Thus, it could be the case that insects are pre-adapted to see vertically polarized light as to not get caught in sap or amber. On the other hand, woodpeckers and sapsucker's diet consists of sap, as well as insects (Pakkala et al., 2018; Beal 1911), along with various other songbirds who also eat insects. If insects are trapped in flowing sap and if sap is polarized, it could be theorized that birds may also be pre-adapted to *see* vertically polarized light to use it as a resource for foraging. This could explain bird habitat dynamics in the conquest for food, and expanding across habitats may increase the variety of birds of whom can detect polarized light cues searching for water, food, and in this case, sap. Studying polarization of windows on a glass building in Hungary, Horváth et al. (2014) found that while the window's polarization attracted caddis flies, it also attracted European magpies who came to the site to forage. Though in an anthropogenic scenario, this observation is very similar to this proposed theory of why birds are attracted to vertical polarized light: insects trapped in 'vertical water' or sap. My study is the first to provide experimental evidence directly supporting phenomenon, though further experimentations need to be conducted to validate my conclusions. Based on this finding, other studies with similar water or sap-like properties should be investigated such as honey or other resin producing plants.

Visible and ultraviolet imagery on painted vinyl show that my simulator mimicked the polarized light cues of water, and even sap, which reinforces my novel results. In the visible range, my treatment could polarize up to 90% of the light hitting the vinyl, which suggests that this was a strong signal. Since my treatments polarized in both the visible and UV ranges, it may be the case that birds could be attracted to vertically polarized light in both ranges. My polarized vinyl proved to the most cost-effective, most durable, and light-weight to use on a long term basis outside in variable weather. If real Maple sap was a viable treatment in the experiment, it would be the most effective treatment, but due to evaporation rate (Williams et al., 2004) it would be inviable on a long term and difficult to manipulate. One major issue with my polarized treatments is that wrapping them around the trees only gives essentially a vertical "sliver" of polarized signal. There would be signal if I had laid the treatments flat as I did when I imaged them. Perhaps hanging the treatments as one would a picture on the North side of the tree may have exposed the polarization cues, but birds would only be able to access and see the polarization on the tree on that one side. Despite this, birds were, on average, attracted to the polarized signal than the non-polarized signal. I conjecture that if a higher surface area of polarization were available, this signal would have been much stronger.

On days of heavy rain and snow, treatments were not well disguised from the other as depolarized treatment became shinier in wetter environments. These days or weather periods were omitted from data collection until later in the day, or the following day according to when the non-polarized treatment dried. Though water repellent would have affected the visual properties of the treatments, a better simulator would have been one that exhibited this feature.

5.6 *Further Caveats and Considerations*

The SECACAM Raptor motion cameras used in this experiment is designed for the best capture of bird movements (Randler & Kalb 2018), though positionality of the camera with the sun's glare impacted photographic data. Even though distance to the tree did not matter in terms of species identification and count, the compass direction in accordance with the tree did matter. Although treatments and suet were placed on the North side of the trees, in which the cameras faced, glare from the sun in the early mornings, mid-afternoons and the evenings resulted in otherwise viable bird counts that were obstructed by the sun's glare. Taller fence posts would have most likely solved this issue, but this was not feasible to carry by foot, which was my means of transportation to each site during the experimental period.

The cameras themselves posed a hindrance on my data in the spring of 2021 experimental period. At site four, the cameras ceased captures for three days during the first round of treatments making for four days where camera traps did collect sufficient data. To remediate this, I did not count the last three days of both the baseline period and the second round of treatments, allowing for a total experimental period of four days (a total of 12) instead of seven per round. At site five, camera traps ceased data collection on the last day of both the baseline and the second round of treatments. At round one of treatments, camera traps only collected data for one day total. However, this error was not noticed until after birds were counted. To avoid human error in a future scenario, SD cards should be downloaded to a computer on a daily basis, regardless if the photography looks correct on the camera traps, to see if the camera traps are functioning properly. Even though with missing days, bird count data were adequately and strangely comparable. Thus, I kept the counts as is. If it had been the case that bird counts in round of treatments were much lower than bird counts in the second round of treatments, I would have changed my interpretation and collection process. In addition, I argue that when visits are comparable between sites, the signal of the treatment, specifically shiny, is much stronger. This is because a larger discrepancy amongst sites or treatments would create more signal or noise, distracting results from the signals of the vertically polarized treatment. Repetition of a similar design I have presented where birds were counted until they were compatible would be the most effective and sufficient means of conducting data collection. Though this only occurred at site five, I conjecture that factors outside the experiment such as bird habitat selection and preferences not related to treatments, discussed in earlier sections, could have influenced count data across six days to be comparable to bird counts on one day.

In the fall 2020 experimental period, birds were counted from sunrise to sunset across seven days for round one and two of treatments, five days for baseline for site two and three, and seven days at site one baseline. I had first theorized that the baseline period does not need to be the same as the treatment period because it is essentially testing for bias rather than strictly the number of bird visitations. However, after analyzing my data from my fall 2020 experimental period, the baseline data needed to be as long as the treatment period for experimental control, despite showing similar, yet different results on how treatments dictate bird attraction. If more resources and time were available, spring 2021 data would have been collected in the same way that fall 2020 data was collected. Instead, spring experimentation bird count data was within the time frame of sunrise (6am-10am) and sunset (5pm-7pm) hours only. Despite smaller time frames, birds were still attracted to the feeder with associated vertically polarized signal, but this was coupled with positionality. It may be the case that since birds are more active during sunrise and sunset hours (Moore 1986), and given that spring is known for migration and mating episodes (Debeffe et al., 2019) attractiveness to polarized light for foraging behavior may be selective.

I analyzed and interpreted fall 2020 and spring 2021 datasets separately for a variety of reasons. First, my methodologies of counting bird visitations were different in the fall and the spring. Though it could be argued that combining these two datasets together would create a stronger signal of treatment and methodologies do not matter, there would be a large discrepancy in the data that may allow for false significances due to the differences in bird visitations counts being higher in the fall overall than the spring. This could be sorted through a GLMM, but other factors would need to be considered. One factor would be missing data in the spring experimental trial. I am effectively measuring bird visits across time. If time (days) are not controlled, comparing the fall to the spring when there are strong mismatches could essentially create results that cannot be justifiable. There would be biases from the lack of keeping time as a control.

Second, different seasons may create different signals. Not only does my data suggest that birds can see vertically polarized light, but it also suggests that birds can see vertically polarized light in the fall and the spring seasons, despite the effects that weather events and temperature may have impacted bird visitations. If analyzed together, I would not be able to see explanatory variable coupling on seasonality, which could create effects with different variables that may not be altogether accurate for my conclusions. Although treatment would most likely been a stronger signal on its own, I conjecture it would not be representative of the relationships with variables such as site or positionality.

Third, my sample size is not sites, but rather, based on my statistical analyses, it is effectively bird counts of various avian species. If my sample size was sites, I would have combined sites together to create a stronger result than just with a sample size of half of those sites. Overall, I argue that this choice essentially makes my results stronger: birds can see vertically polarized light in different seasons, and this suggests that birds use these signals in both seasons to make choices in the environment in how best to guide their feeding behavior.

5.7 *Anthropogenic Disturbances, Management and Conclusion*

Suggested that birds do see polarized light in the vertical, or even horizontal range, navigating the built environment poses serious mortality threats on water-obligate birds. Birds may mistake the side of a glass building (Lao et al., 2020; Zhao et al., 2020), oil waste pits, solar panels (Kosciuch et al. 2020) or asphalt roads (Kriska et al. 2008) for water, as it exhibits similar visual cues (Horváth et al., 2009). This study suggests birds could also mistake similar objects for sap. Ecological traps (i.e., oil waste pits), or scenarios in which animals choose a low quality habitat to settle in, risking survivability, and polarized light pollution (i.e., infrastructure), creates dangerous landscapes for birds who use polarized light cues from water, and even sap, to navigate, orient, and now, forage. Researchers found that instead of colliding into water, Brown pelicans collided with dark pavement (Kriska et al., 2008), and songbirds and pigeons collided with solar panel fields (Kosciuch et al., 2020). One study found that at a particular solar panel field, up to 90% of bird collisions were observed throughout their study design (Kosciuch et al., 2020). Such polarize light cues are especially dangerous for water-obligate birds who use cues to locate bodies of water, but may mistake an artificial polarizer for a natural polarizer.

Though a relatively new phenomena to connect the two cases with one another, mortality of birds from infrastructure has been documented, and it so happens that these human-made objects, byproducts (oil pits) and infrastructure also polarize light (Horváth et al., 2009). Navigating further into researching the associations between animals and natural, but also artificial, objects that polarize light, environmental management tools and technology may need to be implemented in architectural design by urban planners, companies and industries in the near future. Suggestions for solar panel fields may include placing lines on the solar panels (Horváth et al., 2010), or even bioreplicating the microtexture of rose petals onto the solar panel (Fritz et al., 2020). This has been found to reduce the number of insects attracted to the panels. Assuming these textural components can also allow birds to distinguish this from water or sap, it may be advantageous in the future to create design that reduces bird attractiveness in the built environment.

In conclusion, through a field experiment where wild birds were exposed to a choice between a feeder associated with a polarized treatment and a feeder associated with an unpolarized treatment, on average, birds made the choice to go to the feeder associated with the polarized light signal, than the feeder with the depolarized treatment. My analyses reveal that this preference is site and position dependent, and certain species may play a role in this conclusion, but they do not bias the data. The baseline study showed that all previous biases were eliminated when treatments were placed on the tree, with more birds attracted to the conspicuousness of the treatments, and at all but one site, birds chose to go to the polarized treatment over the matte treatment. Natural sap, as well as maple syrup, polarizes light the strongest in the UV range, and there are different strengths of polarization on different types of bark and wood. My polarized treatment was also an adequate simulation for sap and syrup as it was a strong polarizer in both the UV and visible range, while the matte was a strong depolarizer. These novel conclusions provide insight in how birds navigate a complex environment by using polarized cues in the environment, such as sap, to guide their foraging behavior.

A Supplementary Materials and Information

A.1 Text: Raw Data Analyses and Summary

The results of my raw data visualizations in Microsoft Excel suggest that, on average, across all species of birds, more birds visited the tree feeder associated with a vertically polarized light treatment than a tree feeder associated with a vertically unpolarized light treatment over time at five out of six experimental sites (Figure S4). My statistical analyses in R revealed that relationships with bird visitations is much more complex than I had originally conjectured. Though crucial to see my raw data visualizations, any simple statistical measures just between treatments and visitations are particularly insensitive to the various signals and explanatory variables in my experiment. This is why I furthered my data analysis to a multi-step analyses of ANOVAs, Mixed Models and GLMM as measures on count data should not be simply distilled.

These statistical results in my paper show a multi-variable, interconnection of dependencies, that still point to a strong significance in how the implementation of my study design had an effect species of birds attracted to my experiment, and the number of bird visits to treatments. This emphasizes the signal of my results, coupled with explanatory variables such as site and position, as I manipulated wild bird's foraging behavior.

My raw data from the fall 2020 experimental period suggest that birds can see or are attracted to vertically polarized light, as there were more average percent bird visits to the shiny, black, vinyl treatment and its associated food cue than the matte, black, vinyl treatment at all three sites. Baseline data signified more bird visits to each of the three sites after treatments were placed on the tree. Additionally, any beforehand bias birds exhibited during each baseline period was eliminated when the treatments were placed on each tree. More so, birds chose to go to the shiny, polarized treatment over the matte depolarized, treatment at all three sites (Figure S4).

My raw data in the spring 2020 experimental trial suggests that, on average, a higher percentage of birds visit the shiny treatment over the matte treatment (Figure S5). At sites 4 and site 6, results were consistent with that of the fall experimental trial: more average percent bird visits to the shiny, polarized treatment than the matte, treatment. Only was there the opposite pattern at site 5: more visits to the matte than the shiny treatment.

A.2 Table and Figures

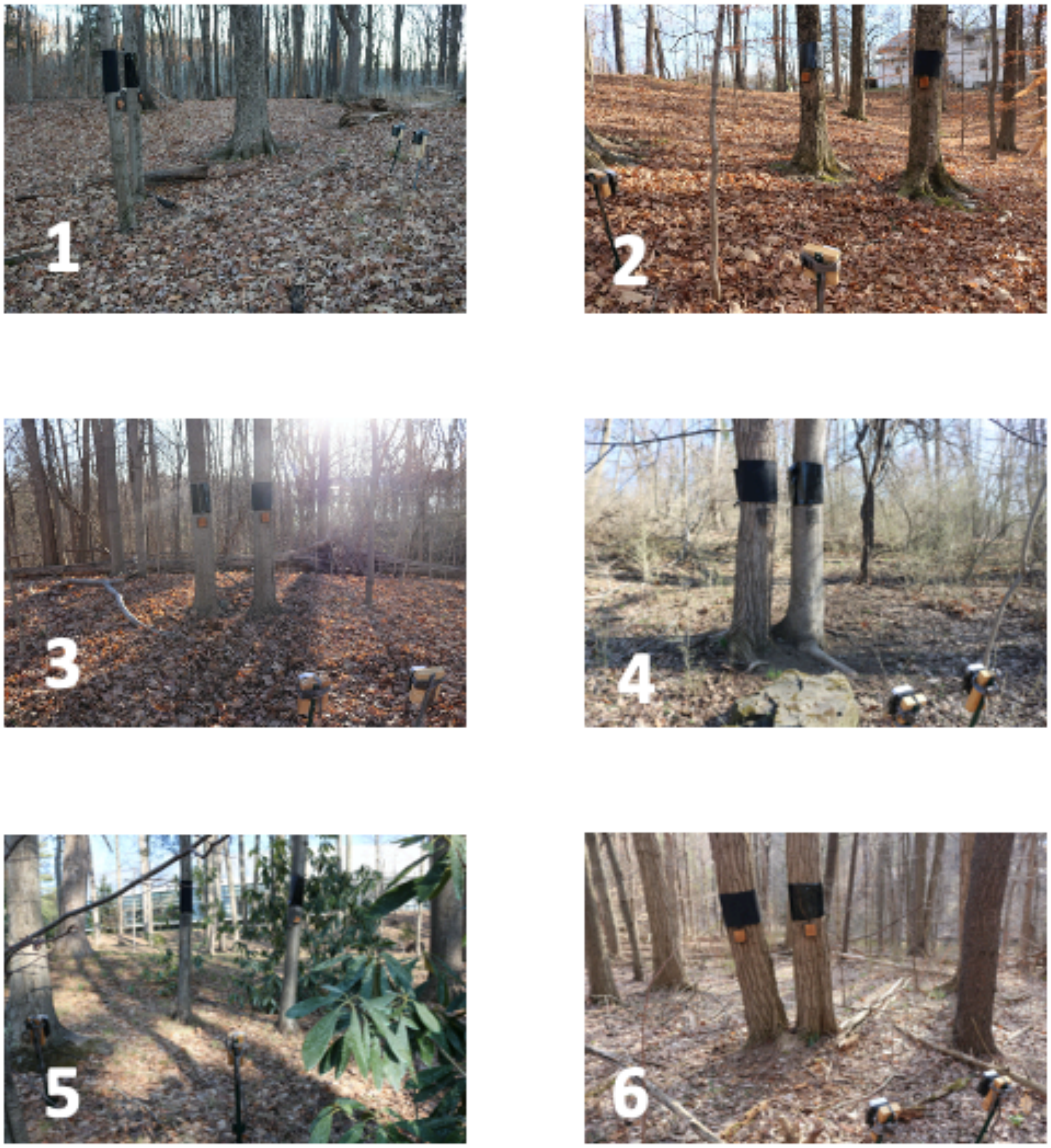
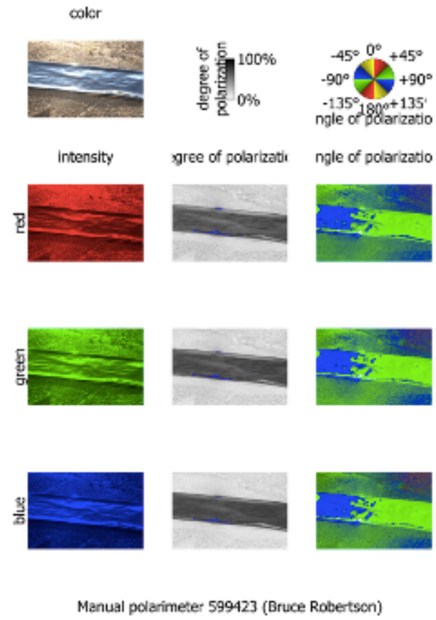
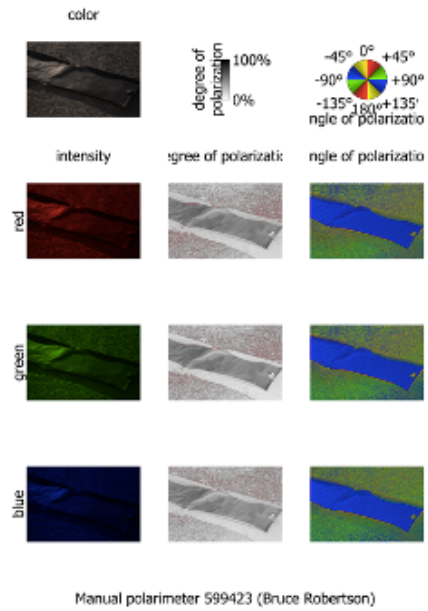


FIGURE S1 Photographs of fall (1-3) and spring (4-6) sites with treatments on tree positions (A and B), associated food-cue, and SECACAM camera operators.

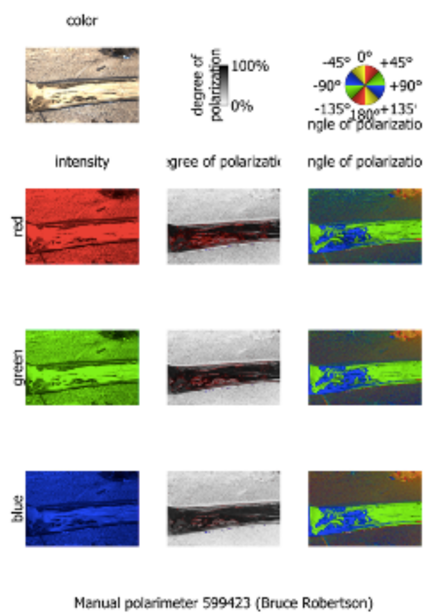
a Visible Shiny Towards Sun



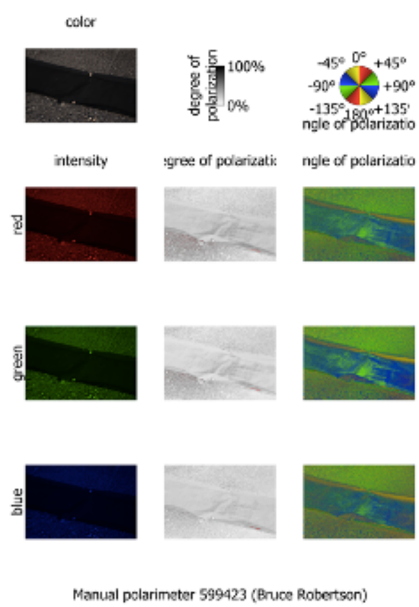
b Visible Matte Towards Sun



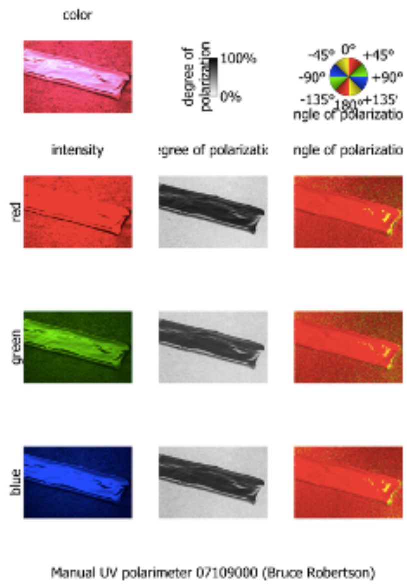
c Visible Shiny Away from Sun



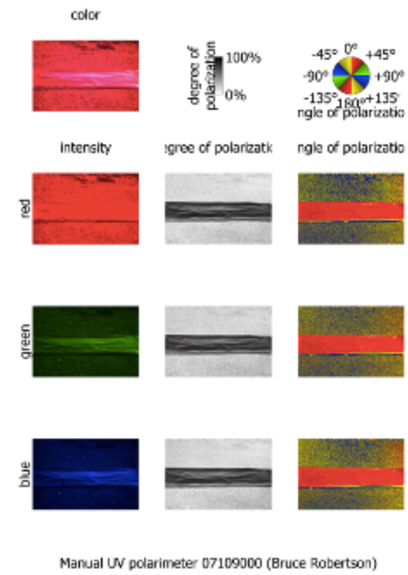
d Visible Matte Away from Sun



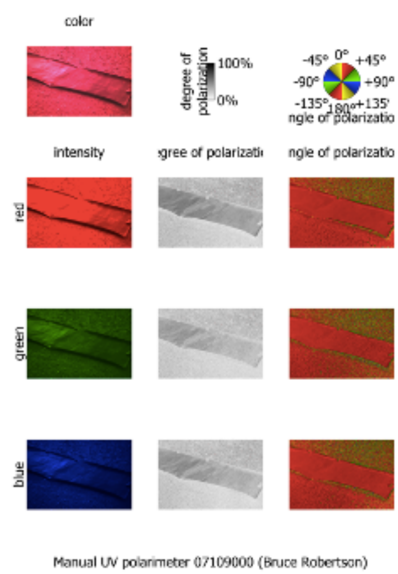
e Ultraviolet Shiny Towards Sun



f Ultraviolet Skylight Shiny



g Ultraviolet Matte Towards Sun



h Ultraviolet Matte Away from Sun

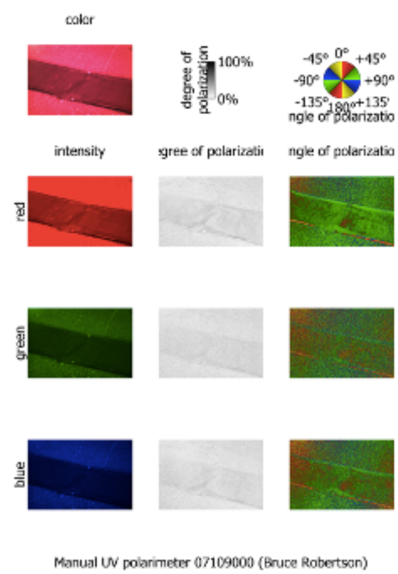
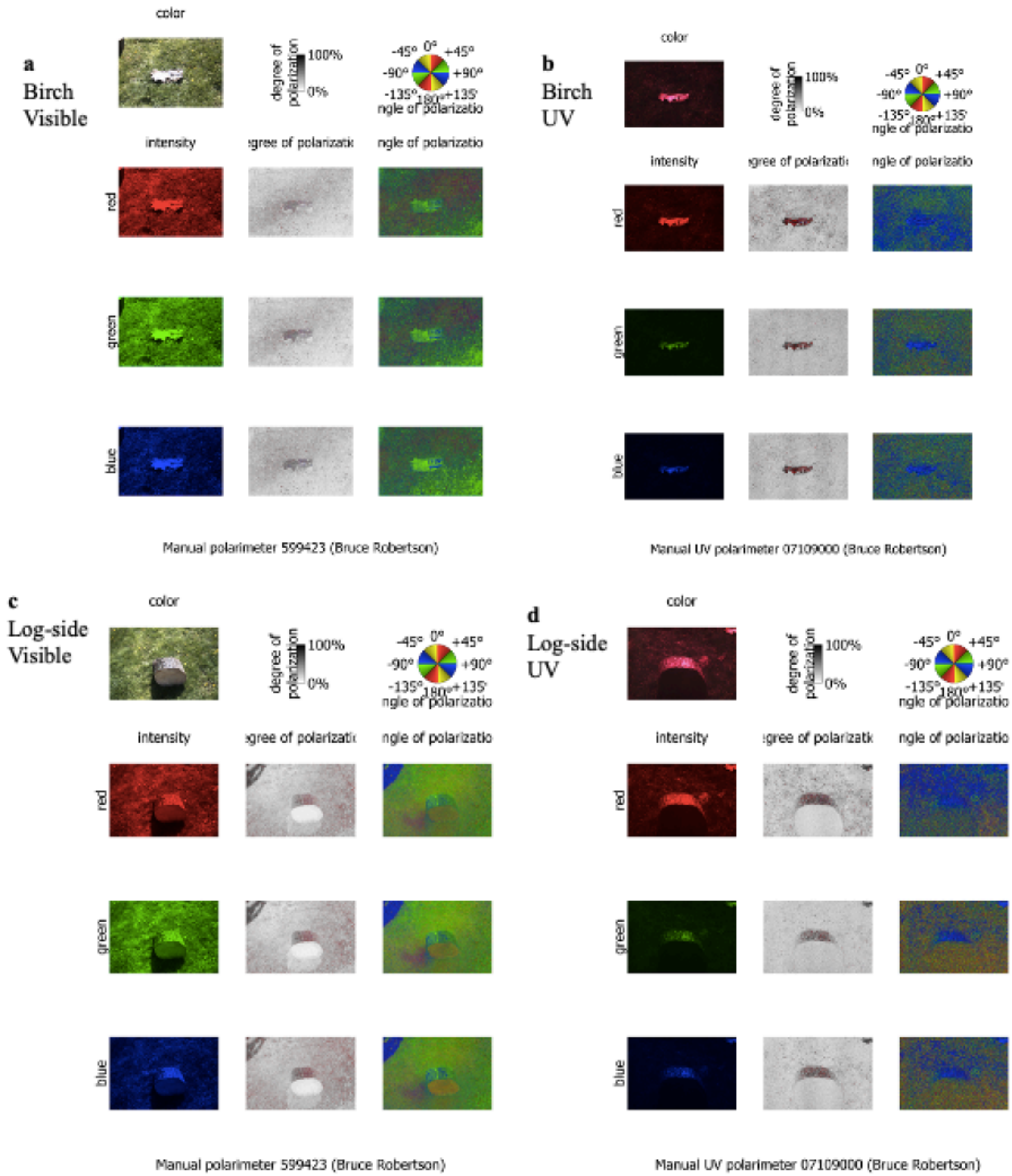


FIGURE S2 Visible (*a-d*), and ultraviolet (*e-h)* comparison of the intensity of polarization, degree of polarization and angle of polarization on treatments in different positions. A Canon DSLR modified camera with a polarization filter to take pictures of treatments in the visible range, and a Nikon DSLR camera modified camera with a crystalized lens to take pictures of treatments in the ultraviolet range, was used. AlgoNet® was utilized to analyze polarization properties of treatments from the pictures taken. Original images are depicted at the top left hand corner, with the degree and angle of polarization legends at the top of the comparison chart.


a
Birch
Visible
color
degree of polarization
100%
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-45° 0° +45°
-90° +90°
-135° 180° +135°
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Manual polarimeter 599423 (Bruce Robertson)
b
Birch
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Manual UV polarimeter 07109000 (Bruce Robertson)
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Manual polarimeter 599423 (Bruce Robertson)
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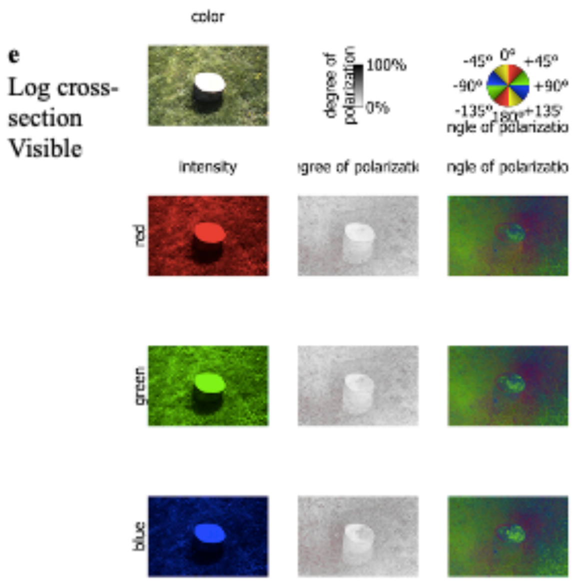
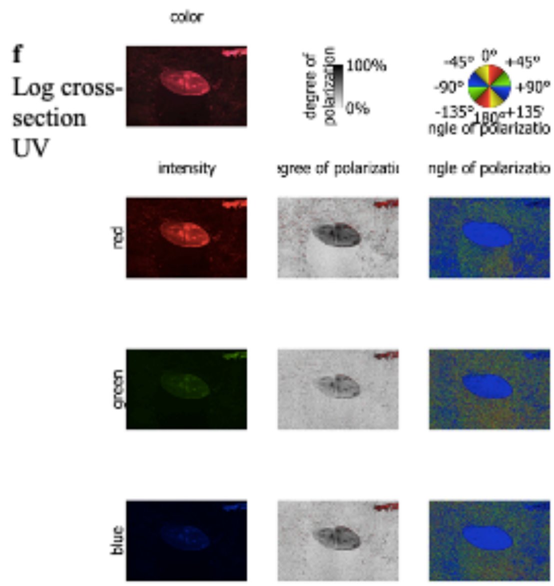
Manual UV polarimeter 07109000 (Bruce Robertson)



Manual polarimeter 599423 (Bruce Robertson)



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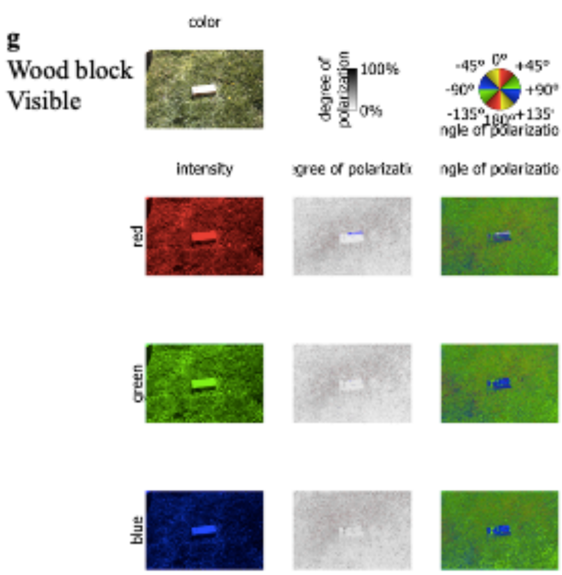
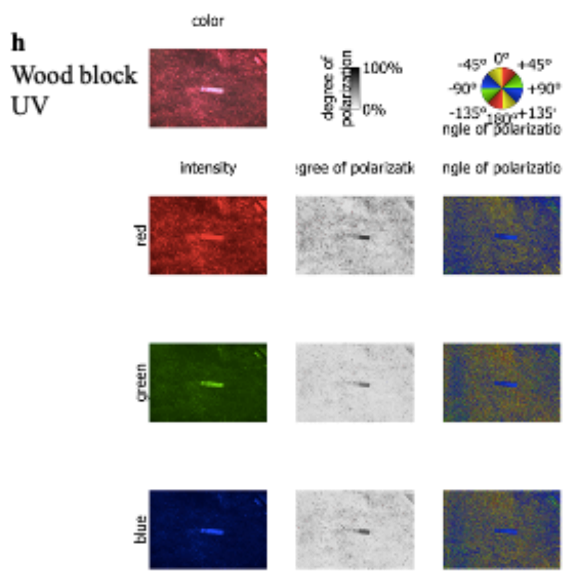


Manual polarimeter 599423 (Bruce Robertson)



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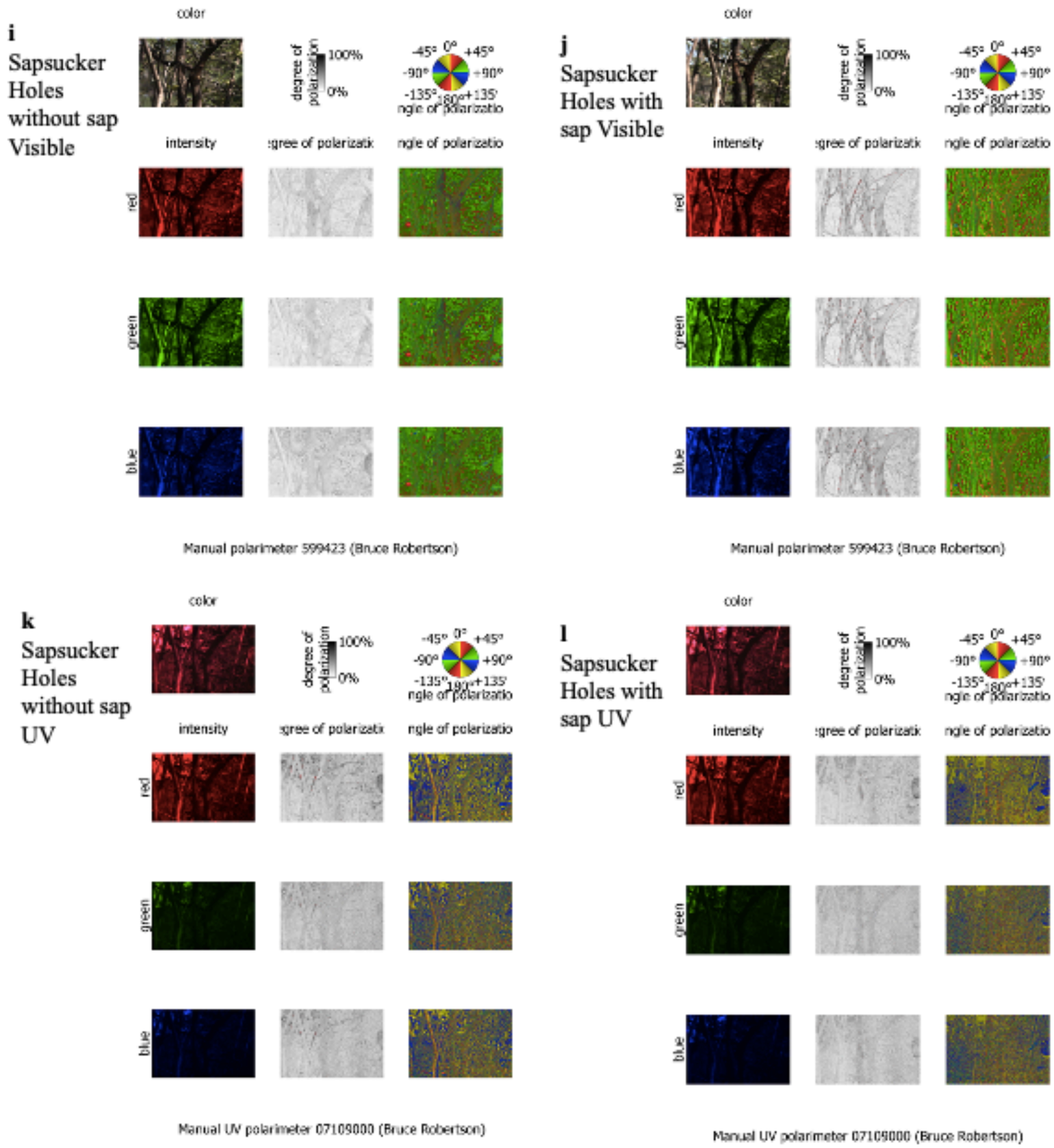

FIGURE S3 Visible and ultraviolet comparison of the intensity, degree and angle of polarization of sap and syrup on different wood and bark objects: Black birch (*a-b*), side of a log (*c-d*), log cross-section (*e-f*), wooden block (*g-h*) and sap was only painted on sapsucker holes (*i-l*). In all but the sapsucker unknown tree, natural Maple sap was always painted on the left side of the object, and Maple syrup was painted on the right. A Canon DSLR modified camera with a polarization filter to take pictures of treatments in the visible range, and a Nikon DSLR camera modified camera with a crystalized lens to take pictures of treatments in the ultraviolet range, was used. AlgoNet® was utilized to analyze polarization properties of treatments from the pictures taken. Original images are depicted at the top left hand corner, with the degree and angle of polarization legends at the top of the comparison chart.

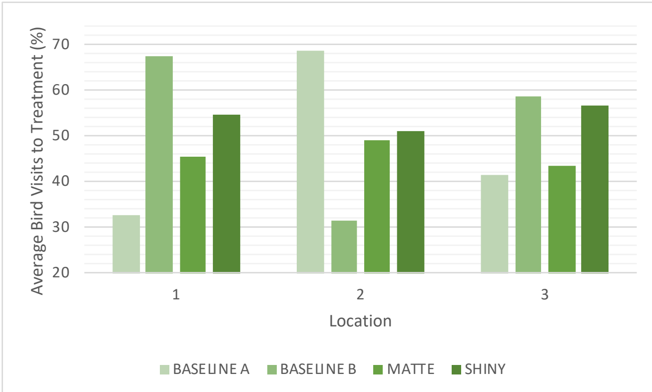

FIGURE S4 Baseline and treatment average percent bird visit data over the course of the fall 2020 experiment at the three experimental sites. Biases or preferences of tree food associations were compared with data from the treatment period. Positionalities (left and right matte, left and right shiny) were combined to form bar graphs. A and B stand for left and right respectively.

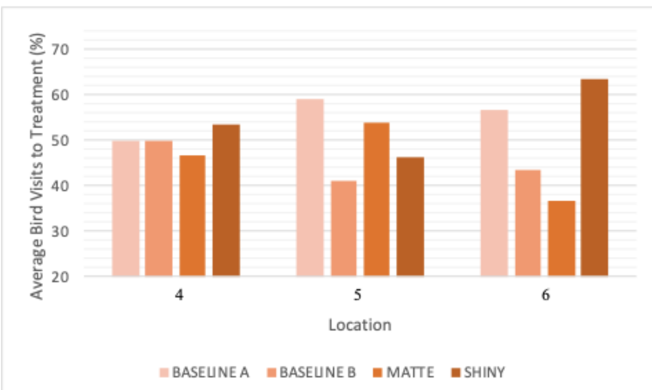

FIGURE S5 Baseline and treatment average percent bird visit data over the course of the spring 2021 experiment at the three experimental sites. Biases or preferences of tree food associations were compared with data from the treatment period. Positionalities (left and right matte, left and right shiny) were combined to form bar graphs. A and B stand for left and right respectively.

Latin Name	Common Name	Site 1	2	3	4	5	6
Poecile atricapillus	Black-capped chickadee	❖	❖	❖	❖	❖	❖
Cyanocitta cristata	Blue jay	❖	❖	❖		❖	
Picoides pubescens	Downy woodpecker	❖	❖	❖	❖	❖	❖
Leuconotopicus villosus	Hairy woodpecker	❖	❖	<❖	❖	<❖	<❖
Colaptes auratus	Northern flicker		<❖	❖	<❖		
Melanerpes carolinus	Red-bellied woodpecker	❖	❖	❖	❖	❖	<❖
Sitta carolinensis	White-breasted nuthatch	❖	❖	❖	❖	❖	❖
Sitta canadensis	Red-breasted nuthatch	❖		❖	<❖	❖	❖
Cardinalis cardinalis	Cardinal		❖		❖	❖	
Junco hyemalis	Dark-eyed junco		❖	❖	❖	❖	
Thryothorus ludovicianus	Carolina wren		❖	❖	❖		
Sphyrapicus varius	Yellow-bellied sapsucker		<❖	❖	<❖		<❖
Sturnus vulgaris	E. Starling			<❖			
Certhia americana	Brown creeper		<❖		<❖	<❖	
Baeolophus bicolor	Tufted titmouse	❖	❖	❖	❖	❖	❖

* ❖ indicate overall visits > 5, <❖ indicate overall visits <5

TABLE S1 All bird species of whom visited sites (suet dough and treatments) for both the fall (1-3), and spring (4-6) experimental periods across positions and treatments. Codes are given for bird counts greater than five and less than five.

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